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TECHNICAL UNCERTAINTY, EXPECTED CONTRACT PAYOFF, AND ENGINEERING DECISIONMAKING IN A SYSTEM DEVELOPMENT PROJECT

F. S. Timson

The RAND Corporation
Santa Monica, California

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Rand
SANTA MONICA, CA. 90406

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SANTA MONICA, CA 90406

PREFACE

The research reported in this memorandum was conducted under the sponsorship of the Advanced Research Projects Agency (ARPA) and is a product of a continuing study of the management of research and development (R&D). It presents a technique for analyzing the effects of alternative policies for decisionmaking and alternative forms of contracts in system development. A computer program for generating histories of decisionmaking in system development is developed and demonstrated. The program emphasizes the information and learning aspects of the development process. This program approach constitutes an alternative method for gaining experience with various policies and contracts.

The program should be of interest to persons who are concerned with the evaluation of policies for decisionmaking and the evaluation of alternative forms of contracts. The conceptual framework should be of interest to all persons involved in the management of R&D, especially in the relation of technical information processing to risk assessment. The technique may be applied to military or commercial development projects.

In addition to the support of The Rand Corporation, this research was partially supported by the Office of Naval Research (Contract No. N00014-67-0111-0010), and, in a different form, also constituted the author's doctoral dissertation.

SUMMARY

The research in this memorandum presents a method for analyzing engineering decisionmaking in a system development project. System development is viewed as having the following characteristics:

- o A system is developed by sequentially executing actions that buy information about the parts of the system.
- o The ultimate determination of the success or value of the final product depends on the characteristics of the whole, not the parts.
- o At any time, the information about the parts and the whole is uncertain.

The method is developed in such a way that it can be used as a tool to evaluate policies for decisionmaking or to evaluate the influence of multiple incentive contracts. The decisionmaking policies examined are organization-oriented rather than individual-oriented. They use system and project characteristics as the criteria for decisionmaking instead of lower level characteristics, or personal goals.

The result is a model in which the component-level physical and performance characteristics and the component-level engineering activities of a system development project are explicitly related to the ultimate results at the system and total program level. In this model activities are performed that yield information about the physical and performance characteristics of the parts of the system. This information is uncertain, and it is expressed in the form of probability distributions. Selection of subsequent activities is based on the impact of the component-level information at the system and total program level; that is, in terms of the impact on system performance, contract payoffs, delivery dates, and program costs. In this memorandum, the uncertainty regarding the system performance and contract payoff is treated explicitly in the decisionmaking process. Delivery dates and program costs are treated using single-valued forecasts.

The research combines engineering and decisionmaking analyses into a simulation model of system development. The simulation model has two

parts: (1) a model of a system development project; and (2) a model of the decision and information processes in system development.

The system development project is characterized by a set of *goals* that are expressed as a preference relationship over system and project characteristics in the form of a multiple incentive contract; a number of *alternative designs* for the components of the system; a number of engineering *activities* that can be conducted on the component designs to improve the state of knowledge regarding the components; and a *state of knowledge* that has two elements: (1) the relationships between the characteristics of the system, the subsystems, and the components; and (2) the knowledge regarding the values of the system, subsystem, and component characteristics.

The model of the decision and information portion of the system development process functions as follows:

1. Actions (engineering activities applied to specific component designs) are evaluated. The details of the evaluation procedure vary from one decisionmaking policy to the next. All policies make some kind of forecast regarding the technical results expected from a component-level action. Some forecasts explicitly account for technical uncertainty and some do not. Propagation of error methods are used to determine the impact of the component-level forecast at the system and total-program level.*
2. Actions are selected sequentially.
3. Actions are executed.
4. Information is received regarding the values of component characteristics. This information is uncertain, and the amount of uncertainty is a direct function of the activity that generated the information.
5. Propagation of error methods are used to determine new knowledge regarding values of the subsystem and system characteristics.

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*This procedure can be described as a dynamic technical risk assessment that is updated every time new information is obtained.

These steps are repeated until a terminal action ends a given project simulation.

In the research reported here, nine decisionmaking policies were considered and five were selected for study using samples of 51 simulated projects. (Policies 2, 3, 7, and 9 were not examined, either because of inherent difficulties or too great a similarity to other policies.) The policies selected for in-depth study represent the following conditions:

1. Policy 1: *Maximize Expected Payoff* is a close approximation to the decision procedure used in sequential decision theory in which the value of a terminal action is compared to the value of an action that buys more information. These calculations are based on the complete probability distributions for the two cases. Thus, it represents a policy that would be recommended by economic decision theorists. The payoff refers to the fee earned under the multiple incentive contract. All other policies are deviations from Policy 1.
2. Policy 4: *Current Means Analysis* differs from Policy 1 in that the evaluation of actions is based on the means of the system performance probability distributions, while Policy 1 utilizes the entire distributions. Hence, Policy 4 is intended to show the effect of using only a single-valued estimate of the outcomes instead of all possible outcomes.
3. Policy 5: *Low-Cost Actions First* differs from Policy 1 in requiring that all of the actions that are low-cost and short-time be done first. There are low-cost actions in all alternative designs, hence, Policy 5 shows the effect of examining all designs early in the project.
4. Policy 6: *Initial Prior Means, Optimistic* differs from Policy 1 in not using all of current technical information. Policy 6 uses current information for the characteristics that will be measured. For the characteristics that will not be measured, the mean values from the beginning of the project are used. Hence, Policy 6 is intended to show the effect of only partial distribution of technical information to decisionmakers.

5. Policy 8: *Probability of Technical Success* differs from Policy 1 in using the probability of technical success as the criterion for selecting actions. Policy 1 uses the expected payoff that includes time and cost considerations as well as the technical performance.

These five policies were examined using two multiple incentive contracts. The zero-incentive points for both contracts were the same and there was only a small difference between the two with regard to the relative weight placed on the system performance characteristics. The major difference between the contracts was the rate of incentive for being over or under the zero-incentive (required) values for the system performance.

An antisubmarine warfare patrol aircraft was used for the system to be developed. The technical performance characteristics used in the incentive contracts are the gross take-off weight and a fuel economy measure. The two contracts and five policies resulted in ten different development cases.

The results were analyzed using two system performance characteristics (gross take-off weight and fuel economy), the program cost and time, the contractor's fee, the sequences of actions, and the frequencies of technical success and failure.

To demonstrate the use of the technique in evaluating decision-making policies and incentive contracts, several conclusions were drawn using the results of the ten sample cases. These conclusions are conditional upon the special example used in this study and should not be taken as evidence regarding the relative merits of the various policies and contracts studied for other projects, technologies, uncertainties, and so on. However, the technique has many other uses, including analysis of impact of multiple incentive contracts on engineering decisions and technical outcomes and generation of probability distributions for cost estimates. Several of these will be briefly discussed at the end of the memorandum.

ACKNOWLEDGMENTS

The author would like to express his appreciation to several members of The Rand Corporation research staff. David Novick and F. S. Pardee stimulated and encouraged my efforts in the topic. Thomas F. Kirkwood, F. S. Pardee, and E. W. Paxson also made comments and suggestions on the content and form of the final result.

I would also like to thank Professors W. J. Abernathy, R. B. Andrews, R. A. Goodman, J. R. Jackson, M. R. Mickey, and J. C. Ries of the University of California at Los Angeles for their help and guidance.

CONTENTS

I. INTRODUCTION

PURPOSE

The purpose of this memorandum is to present a model of engineering decisionmaking in a system development project and to demonstrate the use of the model as a tool for evaluating policies for decisionmaking and multiple incentive contracts. In this work, system development is viewed as having the following characteristics:

- o A system is developed by sequentially executing actions that buy information about the parts of the system.
- o The ultimate determination of the success or value of the final product depends on the characteristics of the whole, not the part.
- o At any time during the development process, the information about the parts and the system is uncertain.

The motivation for this research stems from many previous studies of decisionmaking in research and development (R&D). Policies for decisionmaking in R&D have been the subject of many studies* and some of the policies studied in the present work reflect these earlier studies.

Most past studies have dealt with development decisionmaking in terms of results at the total program level, for example, the system performance, program cost, delivery date, and contractor payoff. However, the alternative courses of action examined in these studies were not "operationally defined"; that is, they did not specify actions that engineers in development organizations actually carry out, thereby obtaining items of information regarding the system. Instead, courses of action such as "work on design A," or "work on design B," or "work on designs C and D" were the alternatives considered. This probably was due to the desire for actions that produced information (or results) at the same level as the evaluation. The resulting studies were

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*See especially, B. H. Klein, W. H. Meckling, and E. G. Mesthene, *Military Research and Development Policies*, The Rand Corporation, R-333, December 4, 1958; and Thomas Marschak, T. K. Glennan, Jr., and Robert Summers, *Strategy for R&D*, Springer-Verlag, New York, 1967.

useful to academicians but of limited value to practicing development decisionmakers.

One contribution of the present research is the combination of the concept of evaluation at the total program level with alternative courses of action defined at the engineering level. This combination should open the way for more and better research on development--research that will be meaningful to both academicians and development decisionmakers.

To demonstrate the unified framework, a computer simulation model of a system development project is constructed. This model has great potential in itself. It is a tool that can be used as a "laboratory" for testing alternative decisionmaking policies and contracts for influencing decisionmaking. The program can be changed to reflect different engineering activities, alternative designs, initial conditions, incentive contracts, decisionmaking policies, and even technologies. Some of these changes require only new input data and others require rewriting parts of the program, but the general approach is the same for all cases. Any number of project histories can be obtained for each set of conditions. Thus, large samples can be generated and statistical evaluation techniques used. The model is described in terms of two sets of elements that have been identified as "engineering considerations" and "management considerations."

ENGINEERING CONSIDERATIONS

The engineering aspects of the project constitute the inputs to the model and include the items described below.

Goals

The goals of a system development project are represented by a multiple incentive contract over time, cost, and system performance. Values for the contract terms are read in as input data.

Alternatives

The alternatives that are available refer to the various designs and configurations for the components, subsystems, and the system.

They are characterized by probability distributions over the values of the characteristics of each part (e.g., component, subsystem, etc.). These probability distributions bear an important relationship to each other as described under the Hierarchy of Uncertainty heading below.*

Activities

The activities are engineering processes that buy information about the characteristics of the alternatives. Activities may be applied at various levels (e.g., component, subsystem, or system). An activity is characterized by a time, a cost, the characteristic(s) measured, and the precision of the measurement. Values for these items are read as input data.

The State of Knowledge

The state of knowledge refers to what is known at any given time about the system being developed. There are two important aspects to the state of knowledge.

- *Technology*. The equations that specify the functional relations between the physical and performance characteristics at all levels (e.g., component, subsystem, and system) form one part of the state of knowledge. This research assumes that these equations are known and not subject to any uncertainty. The model of system development uses this body of equations to establish the Technical Information Subsystem of the management system.
- *Hierarchy of Uncertainty*. As specified above, each alternative is represented by probability distributions over the characteristics of the alternative. The distributions at adjacent levels are related by the design equations. The uncertainty hierarchy

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*To avoid any semantic difficulties, these alternatives should not be referred to as alternative courses of action. Actions constitute the application of some engineering activity to some alternative. For example, wind tunnel testing is an *activity*, wing design number 1 is an *alternative*, and doing a wind tunnel test of wing design number 1 is an *action*.

at the start of the development project is determined by applying the Technical Information Subsystem to probability distributions for the lowest level characteristics. These initial, low-level distributions are read in as input data. The hierarchy is subject to revision as information is learned by carrying out activities on alternatives (executing actions). There are as many hierarchies as there are system designs. Propagation of error methods are used to update the appropriate hierarchy.

MANAGEMENT CONSIDERATIONS

The management aspects of a system development project constitute a complete management information and decision (command and control) system. Two major elements of the management system are identified below.

Technical Information Subsystem

The Technical Information Subsystem is the body of equations that specify the relationships between the characteristics at the various levels. In the present work it is expressed by the propagation of error expressions derived from the set of design equations (called the Technology).* These expressions are embodied in a hierarchical set of subroutines in the program.

Decisionmaking Policies

A decisionmaking policy is a collection of rules used to evaluate and select actions. Three elements of a decisionmaking policy are identified as follows:

- *Eligibility Rule.* The first consideration in action selection is a means for determining which of all possible actions can and may be considered for selection at any given decision point.

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*A system using the design equations and a Monte Carlo computer routine is described in F. S. Timson, *Measurement of Technical Performance in Weapon System Development Programs: A Subjective Probability Approach,* The Rand Corporation, RM-5207-ARPA, December 1968.

This includes both the physical or logical feasibility and management preference.*

- *Forecasts.* The second consideration is what information will be used to evaluate those actions that are eligible. This includes the portion of the current available information that will be used for making time, cost, and performance forecasts. Time and cost forecasts do not include uncertainty in the present work.† Some performance forecasts explicitly account for technical uncertainty and some do not. Propagation of error methods are used to determine the impact of the component-level forecast at the system level.‡
- *Evaluation Rule.* The third consideration is the criterion function that will assign values to the eligible actions using the forecast information.

EXECUTION OF ENGINEERING ACTIONS

The decisionmaking portion of the system development process sequentially selects engineering actions that buy information about the characteristics of the alternatives. When an action is selected, the model determines a new state of knowledge for the characteristic(s) measured. The time and cost of the action are recorded. The Technical Information Subsystem then determines the new values for the characteristics at higher levels of the appropriate hierarchy of uncertainty.

Outputs

The model simulates the history of engineering activities in a system development project. The information available at the end of a project simulation is divided into the following two categories:

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*The relation of eligibility rules to *scheduling* of activities will be discussed in Sec. III.

†This procedure can be described as a dynamic technical risk assessment that is updated every time new information is obtained.

‡Inclusion of uncertainty regarding times and costs is discussed in Sec. VII.

- *The Final State of the Development Process.* The final state of the development process includes (1) values for the system performance characteristics, (2) the identification of the system design that was delivered, (3) the time of delivery, (4) the sum of the costs of all activities undertaken, and (5) the payoff to the contractor.
- *The Development History.* The program presently keeps track of two items in the development history. (1) It lists the actions taken, in sequence. It identifies the activity performed and the design and part of the system worked on. (2) The system performance probability distributions for all possible system designs are provided at each decision point.

The model can be run any number of times to collect a sample of values for all the output items.

APPLICATIONS

The model is most useful for evaluating the impact of alternative decisionmaking policies and multiple incentive contracts on the results of a system development project. This application is demonstrated in this memorandum. Several other uses of the model--including the real-world management of system development, the analysis of multiple incentive contracts, and the production of cost estimates that include uncertainty--are discussed in the last section.

OUTLINE OF MEMORANDUM

The engineering considerations and the details for the specific project used in this research are presented in Sec. II. A general discussion of the management considerations and execution is presented in Sec. III. The decisionmaking policies are described in Sec. IV.

Summary data on the results obtained under the various policies and contracts are presented in Sec. V. Section VI presents the analyses of the policies and contracts, and some conclusions drawn from these analyses are suggested in Sec. VII. Supporting materials are presented in the appendices.

II. THE ENGINEERING CONSIDERATIONS IN A SYSTEM DEVELOPMENT PROJECT

This section discusses the engineering considerations in a system development project and presents the detailed description of these items for a hypothetical development project. The system development project used in this research is for an antisubmarine warfare (ASW) patrol aircraft. This type of project was chosen because the technology is well understood, sources were available to help with defining the elements of the hypothetical project, the data involved are non-proprietary and unclassified, and the system performance characteristics that indicate the aircraft's mission capability are relatively easy to put into analytical form.

GOALS

All system development programs have a purpose. This purpose is expressed in the form of goals regarding the final outcome of the program. For the hypothetical development program used in this study the following attributes of the final state are considered: (1) two performance characteristics of the aircraft, (2) the time of delivery, (3) the cost of the program--exclusive of fee, and (4) the fee paid to the contractor.

System Performance

The system performance characteristics that are used in the contract should be good indicators of the system's mission capability. In addition, the characteristics must be measurable and the method of measurement must be agreed on and specified in advance. For aircraft, certain performance characteristics depend on atmospheric conditions. Because these conditions vary from day to day and place to place, it is necessary to specify the conditions to be used for performance evaluation and the means for correcting for deviations in actual conditions when variations occur.

An ASW patrol aircraft can perform several different patrol missions. The aircraft's ability to carry out these missions is enhanced by its ability to cover large expanses of ocean and to remain on station for long periods of time. The best system performance characteristics to indicate mission capability are thus range and endurance. However, from the point of view of this study, it is not possible to express these characteristics in an analytical form that can be used with the propagation of error technique.

Two substitute performance characteristics are used instead. These are a measure of fuel economy and the gross take-off weight. The fuel economy measure is the number of nautical miles that the aircraft travels per pound of fuel consumed at a given set of flight conditions. These conditions include the aircraft's instantaneous gross weight, the number of engines operating, the speed of the aircraft, the atmospheric pressure and the temperature. The aircraft-related flight conditions are chosen to correspond to one particular mission and the atmospheric conditions are chosen to correspond to this mission on a "standard day."* For the hypothetical project used in this study a low altitude loiter patrol was chosen. This mission corresponds to the following set of values: (1) aircraft gross weight at time of mission = 100,000 pounds, (2) number of engines operating = 2, (3) aircraft speed = 200 knots, (4) atmospheric pressure = 28.33 inches of mercury, and (5) temperature = 513.4 degrees Rankine. The mission description is summarized as follows:

Item	*Description or Value*
Aircraft type	4-engine turboprop ASW patrol
Mission	Low-altitude search
Altitude	1500 ft
Airspeed	200 kn
Number of engines operating	2

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*A "standard day" is a day on which the atmosphere exhibits the properties shown in a Standard Atmosphere Table. Such a table shows pressure, pressure ratio, temperature, density, specific weight, density ratio, the speed of sound, and the kinematic viscosity as a function of altitude. See Courtland D. Perkins and Robert E. Hage, *Airplane Performance Stability and Control,* John Wiley & Sons, Inc., New York, 1949, pp. 481-483. The "standard day" is used as a basis for almost all aircraft performance analysis.

The gross take-off weight is related to the aircraft's mission capability in the following way: The aircraft is designed to operate at a given gross take-off weight that includes a certain amount of fuel. If the actual gross take-off weight exceeds the design gross take-off weight, there are two general courses of action: (1) Use the existing airframe, but trade off fuel and payload, which will, of course, degrade mission capability; or (2) at the expense of additional time and money, develop another airframe, in the hope it will provide the desired capability.

Time

Incentive contracts may relate fee to a number of different contract performance times corresponding to the accomplishment of certain "milestones" by the contractor. In this study, only one time is considered--the time of delivery to the customer.

Cost

The cost used in this study is the cost of carrying out the contract, but excludes the fee earned. It is the sum of material-resources cost, salaries and wages, overhead, etc.

Contracts

A common technique that is used to specify goals and tradeoffs in military system development is the multiple incentive contract. The final state attributes that are included are: some measure, or measures, of system performance; the time required to complete development; and the amount of money spent. The contract specifies for various combinations of performance, time, and cost the fee the contractor will receive.

The general form of the contracts considered in this study is given by

$$TIP = CP + TP + PP^{*} \tag{1}$$

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*The symbols used here are those used in the FORTRAN program with the exception that some quantities symbolized in this study are not used in the program.

where TIP = the total incentive payoff,

CP = the cost payoff,

TP = the time payoff,

PP = the performance payoff.

The cost term determines the portion of the total cost paid by the contractor; hence, it is not a "payoff" in the positive sense. In this work an 80-20 cost-sharing ratio is used.* Suppose that the target cost is $1 billion. Then, if the actual cost is $1 billion or anything less, the contractor pays 20 percent of the cost and the customer pays 80 percent. If the actual cost is more than the target cost, the contractor pays 20 percent of $1 billion plus 100 percent of the cost above it, and the customer pays 80 percent of $1 billion. The cost payoff has the general form

$$CP = \begin{cases} -.2CA, & \text{if} \quad CA \le CR, \\ -CA + .8CR, & \text{if} \quad CA > CR, \end{cases} \tag{2}$$

where CA = the actual cost at the end of the project,

CR = the "target" cost.

The time payoff has the general form

$$TP = \begin{cases} RT(TR - TA), & \text{if} \quad TR \gtrsim TA, \\ -CT(TA - TR), & \text{if} \quad TR < TA, \end{cases} \tag{3}$$

where RT = the amount of reward per unit of time for delivery before the target date,

CT = the amount of penalty per unit time for delivery after the target delivery date,

TA = the actual delivery date,

TR = the target delivery date.

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*See *Department of Defense Incentive Contracting Guide*, U.S. Government Printing Office, Washington, D.C., 1965, pp. 16-18. Note that the scheme used in the present study does not use a maximum and minimum fee limit.

The performance payoff consists of two parts, one for each of the two system performance characteristics; hence, PP can be written as

$$PP = PPNMI + PPGTO, \tag{4}$$

where $PPNMI$ = the performance incentive for fuel economy,

$PPGTO$ = the performance incentive for gross take-off weight.

The fuel economy incentive is given by

$$PPNMI = \begin{cases} RPSNMI(PSANMI - PSRNMI), & \text{if} \quad PSANMI \geq PSRNMI, \\ -CPSNMI(PSRNMI - PSANMI), & \text{if} \quad PSANMI < PSRNMI, \end{cases} \tag{5}$$

where $RPSNMI$ = the reward per unit of performance for fuel economy greater than the target fuel economy,

$CPSNMI$ = the penalty per unit of performance for fuel economy less than the target fuel economy,

$PSANMI$ = the actual fuel economy as measured by the test procedure agreed to when the contract was made,

$PSRNMI$ = the target fuel economy.

The gross take-off weight incentive is given by

$$PPGTO = \begin{cases} RPSGTO(PSRGTO - PSAGTO), & \text{if} \quad PSRGTO \geq PSAGTO, \\ -CPSGTO(PSAGTO - PSRGTO), & \text{if} \quad PSRGTO < PSAGTO, \end{cases} \tag{6}$$

where $RPSGTO$ = the reward per unit of weight for gross take-off weight less than the target value,

$CPSGTO$ = the penalty per unit weight for gross take-off weight greater than the target value,

$PSAGTO$ = the actual gross take-off weight as measured by the test procedure agreed to when the contract was made,

$PSRGTO$ = the target gross take-off weight.

The contract is thus specified by giving values to the quantities *CR*, *RT*, *CT*, *TR*, *RPSNMI*, *CPSNMI*, *PSRNMI*, *RPSGTO*, *CPSGTO*, and *PSRGTO*. Values of these quantities for the contracts considered in the study are shown in Table 1.

Contracts Selected for Study

Contract NEUT × 10 (also labeled Contract B) was selected for use in the large-sample runs because the preliminary results indicated that longer searches for technically superior systems were experienced with this contract. Contract GTO + 1 (also labeled Contract A) was selected because more different system designs were selected with this contract than with any of the others. The rate of incentive on system performance for Contract NEUT × 10 is ten times as much as for Contract GTO + 1. Hence, Contract NEUT × 10 will be referred to as the high incentive contract and Contract GTO + 1 will be referred to as the low-incentive contract.

Relation to Utility Functions

Figures 1 and 2 show the lines of constant performance incentive payoff for Contracts A and B. To anyone that is familiar with the indifference curve used in utility theory,* the parallel between multiple incentive contracts and utility functions for multi-attributed alternatives should be obvious. In fact, the only difference is the spacing between the lines of constant payoff and the corresponding lines of constant utility. There are three distinguishable cases. First, if payoff equals utility, then, the utility map and the payoff map are identical. Second, if the utility for money is a linear function, then, the ratio of the distances between curves of constant payoff and the corresponding utility curves will be a constant. This constant will be equal to the inverse of the slope of the utility for money. The third case is a nonlinear utility for money. In this case, for a payoff map

*See George J. Stigler, *The Theory of Price*, rev. ed., The Macmillan Company, New York, 1952, Chap. 5.

Table 1

SUMMARY OF VALUE OF QUANTITIES IN CONTRACTS CONSIDERED

Quantities	Contracts					
	NEUT	*NEUT* × *5*	*B* *High Incentive* *NEUT* × *10*	*NMI* × *2*	*GTO* × *2*	*A* *Low Incentive* *GTO* + *1*
Target delivery date (TR), wks	126	126	126	126	126	126
Target cost (CR), $	304,671,000	304,671,000	304,671,000	304,671,000	304,671,000	304,671,000
Reward for pre-TR delivery, $/wk	333,330	333,330	333,330	333,330	333,330	333,330
Penalty for post-TR delivery, $/wk	333,330	333,330	333,330	333,330	333,330	333,330
Target fuel economy (PSRNMI), n mi/lb	.088	.088	.088	.088	.088	.088
Target gross take-off weight (PSRGTO), lb	130,000	130,000	130,000	130,000	130,000	130,000
Reward for greater than PSRNMI, $ ÷ n mi/lb	357,000,000	1,785,000,000	3,570,000,000	714,000,000	357,000,000	357,000,000
Reward for less than PSRGTO, $/lb	2,500	12,500	25,000	2,500	5,000	3,500
Penalty for less than PSRNMI, $ ÷ n mi/lb	481,000,000	2,405,000,000	4,810,000,000	962,000,000	481,000,000	481,000,000
Penalty for greater than PSRGTO, $/lb	1,430	7,150	14,300	1,430	2,860	2,500
Fixed fee, $	75,000,000	25,000,000	25,000,000	75,000,000	75,000,000	75,000,000

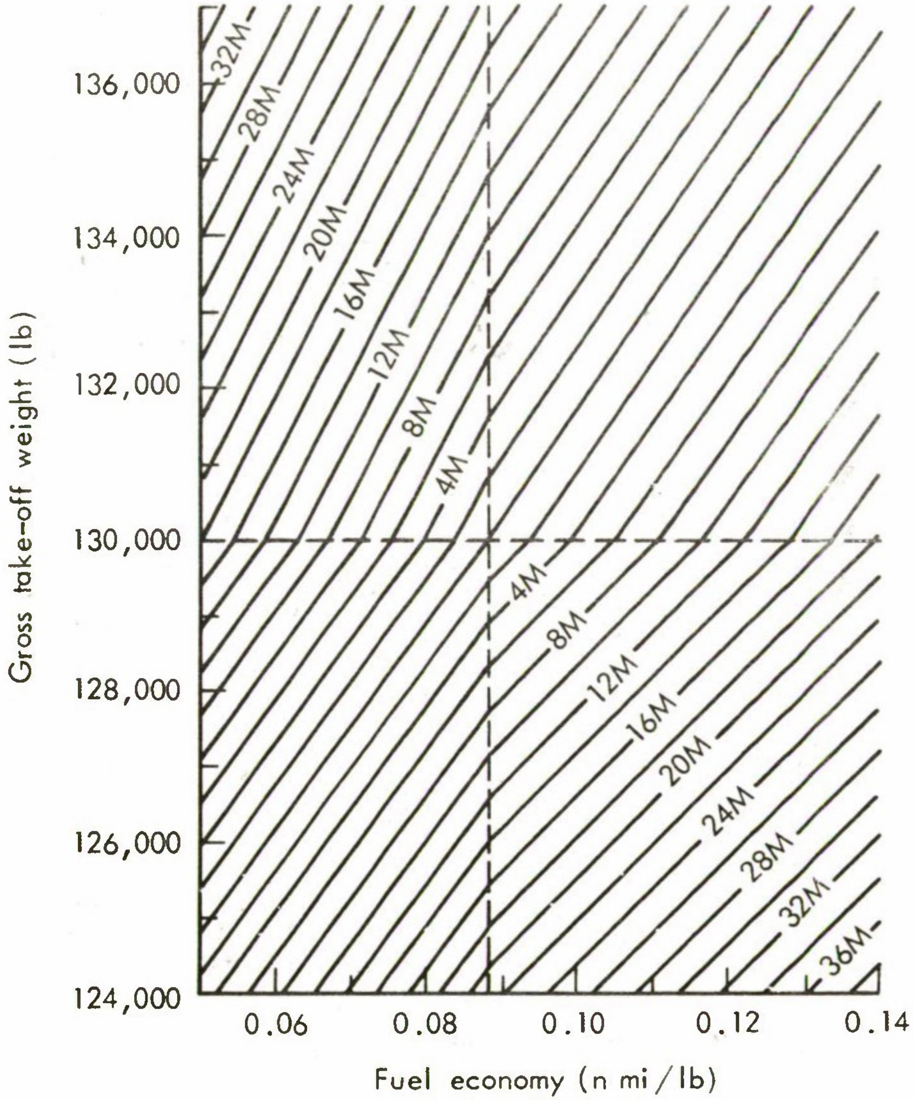

Fig. 1--Constant performance incentive payoff lines for Contract A

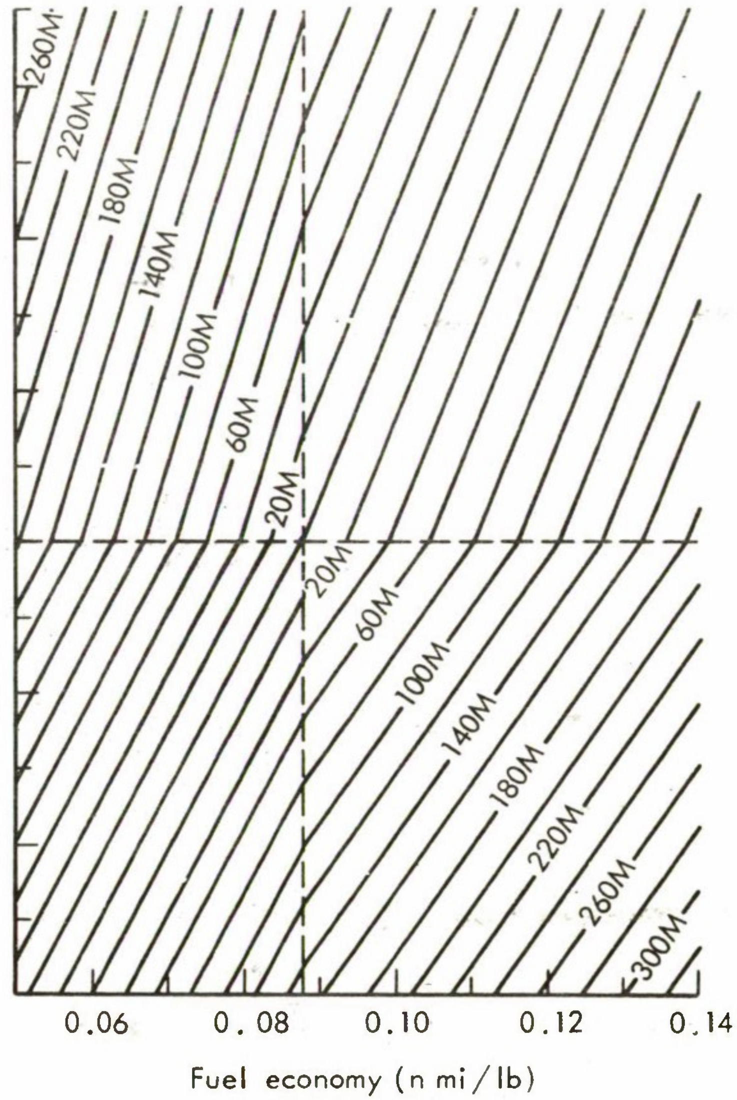

Fig. 2--Constant performance incentive payoff lines for Contract B

that has curves separated by a constant amount, the corresponding utility curves will get closer together or farther apart depending on the local value of the second derivative of the utility for money.

ALTERNATIVES

In almost all system development projects there will be more than one possible design for at least one part of the system. As the various designs for the components are investigated through the engineering activities, it is learned which designs are "best." The determination of the "best" design for all the components rests on simultaneous consideration of the effects of all the components on total system performance.

Call the parts of the system "components," and suppose the system consists of n components. Suppose that each component c_i has m_i alternative (competing) designs. Denote the *jth* alternative for component i by c_{ij}. One possible system design would be c_{11}, c_{21}, ..., c_{n1}. This system design consists of the number "1" design for each component. Call each such system design a "combination," then there are

$$\prod_{i=1}^{i=n} m_i$$

possible combinations for the system (assuming that none of the combinations are infeasible).

A combination is distinguished from a "configuration" because a configuration is concerned not only with which component designs are present, but where they are located with respect to each other. For example, the wing on airplanes can be positioned high on the fuselage, low on the fuselage, or somewhere in between. Each position results in a different configuration.

In the present study, position will not be considered as an element of choice in the decision process. This assumes that the "best" relative position for each component has been previously determined.

In the hypothetical development program, the aircraft is considered as having three major subsystems: the engines, the airframe, and all other subsystems--electronics, hydraulics, stores, fuel, crew, etc. The airframe is further broken down into two major components: the fuselage and tail, and the wing and nacelles. This breakdown is shown in Fig. 3.

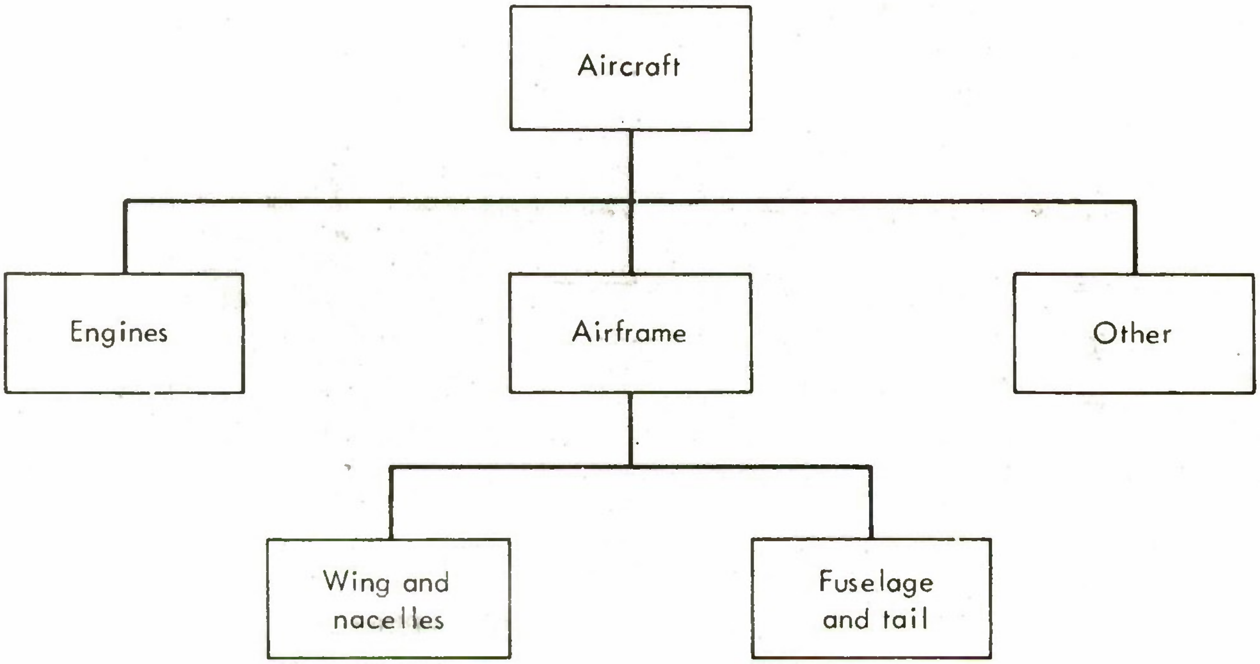

Fig. 3--Subsystem and component breakdown of aircraft

The subsystems for which alternative designs are available are the engines and the airframe. All items in the "Other" category are assumed to be off-the-shelf items. There are 4 airframe alternatives. The model of the system development process simulates the development of the airframe from 4 wing designs and 1 fuselage design.

The development project thus consists of the development of an airframe that is to carry a specific payload, crew, and fuel load and the selection of an engine to go with the airframe.

ACTIVITIES

The activities in a system development project may be classified in the following categories:

- o Building models.
- o Building the real item.
- o Buying information from an outside source.

The first category includes physical models, such as breadboards, mock-ups, scale models,* etc.; and "paper" models, such as stress analyses, simulations, etc. In the present research, analysis of the information obtained from such activities is included in the decisionmaking process as described in the next section.

For the purpose of the present research, the activities are classified into the following categories and are detailed later:

- o *Terminal activities.* Deliver the best of any previously assembled system.
- o *Assemble and test activities.* Build the entire system (for a given configuration) and test it.
- o *Experiment activities.* Build, test, and evaluate a model of the system or of some part of the system.

Buying information from an outside source will be ignored in the present study because it requires some model of the state of knowledge at various times available from an outside source.

Each "experiment" is characterized by (1) the object of the experiment (i.e., a part, component, etc.) and the characteristic(s) measured; (2) a cost to perform, assumed to be known from past experience and independent of the values of the characteristics of the object; (3) a time to perform, also assumed known and independent of the values of the characteristics; and (4) the effect the action will have in determining a new variance for each characteristic measured, also assumed known.† The new variance will be called the posterior variance.‡

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*A model may be full-scale. It is distinguished from the real item by whether it incorporates all features of the real item.

†The effect of the action on the new variance is expressed by the coefficient of variation. Hence, an action is said to measure some quantity with a precision of plus or minus some percent. This procedure is at least partially justified in the present research because a major portion of system development is engineering and in engineering the precision of an experiment is fairly well known ahead of time.

‡Note that the prior distributions are characteristics of the objects of the action, as described later in the text.

These four elements constitute an implicit definition of an "experiment" action.

Each "assemble and test" is similarly characterized with one major difference; the expected new variances for all characteristics are zero, because, when the object is tested, the values of its characteristics will be known with certainty (for the test conditions).*

Terminal actions are characterized by a time and cost to complete the delivery. The system performance characteristics are known with certainty from the corresponding assemble and test (for the test conditions).

The objects of the activities are the parts of the system and the whole system. When an activity is applied to a given alternative design of some part of the system, the activity-object pair will be called an *action*.

For the hypothetical development project used in this research, only a small portion of the activities involved in the development of an aircraft is considered. The two performance characteristics that are used in the multiple incentive contract served as a guide to reducing the number of activities to be included. Activities of interest are those that are concerned with the aerodynamic characteristics and the weight of the aircraft.

The activities are further categorized by the part of the system to which they are applied. Hence, the weight-related activities include: weight estimation for fuselage and tail, weight estimation for wing and nacelles, stress analysis for fuselage and tail, stress analysis for wing and nacelles. The aerodynamic-related activities include: wind tunnel test of a small-scale model of the entire aircraft, wind tunnel test of a large-scale model of the entire aircraft, wind tunnel test of a large-scale model of the wing and nacelles, and wind tunnel test of a large-scale model of the fuselage and tail with stub wings for interference effects. Two additional activities are required to obtain the finished product and to terminate the process: assemble and test the

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*The test conditions are important because they will be the conditions used to determine the values of the characteristics of the final product.

complete aircraft, and deliver the aircraft to the customer. The time, cost, and precision figures are summarized in Table 2. The activities are briefly described as follows:

Table 2

SUMMARY OF ACTION CHARACTERISTICS

Activity	*Object*	*Characteristic(s) Measured*	*Time (wks)*	*Cost ($)*	*Precision (%)*	*No. of Possible Actions and ID Nos.*
Deliver	Complete aircraft	---	1	1,000	--	8, nos. 1-8
Assemble and test	Complete aircraft	Fuel economy, gross take-off weight	52	300,000,000	0	8, nos. 9-16
Wind tunnel, large aircraft	Complete aircraft, including engines	Drag coefficient for aircraft, efficiency factor	20	3,000,000	7	8, nos. 17-24
Wind tunnel, small aircraft	Aircraft excluding engines	Drag coefficient for airframe, efficiency factor	5	160,000	10	4, nos. 25-28
Weight estimation	Wings and nacelles	Weight of wing and nacelles	1	5,000	10	4, nos. 29-32
Wind tunnel, large wing	Wings and nacelles	Drag coefficient for wing and nacelles, efficiency factor	10	500,000	3	4, nos. 33-36
Stress analysis	Wings and nacelles	Weight of wing and nacelles	16	500,000	3	4, nos. 37-40
Weight estimation	Fuselage and tail	Weight of fuselage and tail	1	5,000	10	1, no. 41
Wind tunnel, large fuselage	Fuselage and tail	Drag coefficient for fuselage and tail	10	500,000	3	1, no. 42
Stress analysis	Fuselage and tail	Weight of fuselage and tail	10	200,000	3	1, no. 43

NOTE: The figures have been derived from estimates made by professionals who have been involved in aircraft development. The final numbers were determined by adjusting the individual estimates so that the entire set was "reasonable" from both an absolute and a relative point of view.

The measure of precision used in this research is the coefficient of variation, which is equal to the standard deviation divided by the mean. The figures are expressed as percentages in the table.

- *Weight Estimation*. The weight estimation activity envisaged in this study involves about 5 technical people and requires approximately 1 week of time. The figures for time, cost, and precision are: (1) time equals 1 week; (2) cost equals $5000; and (3) precision equals 10 percent of the estimate. (Precision refers to the estimate of the weight of the structural member only and does not include electrical, hydraulic, or any other equipment weights.)
- *Stress Analysis*. The stress analysis activity involves more. Hundreds of people are involved over a longer period of time and the precision of the resulting weight figure is much better. The purpose of the stress analysis is to determine how the airframe is to be built so that it will be structurally sound. Once a sound design is worked out, the weights of all cubic inches of material are added up to get the total weight. The time required for stress analysis is 10 weeks. The cost for the fuselage and tail is $200,000 and for the wing and nacelles it is $500,000. The cost for the wing analysis is higher because increased technical effort is required. The precision of the weight obtained is 3 percent.
- *Wind Tunnel: General*.* Wind-tunnel testing generates information about many aerodynamic characteristics of an aircraft. The many detailed measurements are used to evaluate the aircraft's lift-drag performance, its stability and control characteristics, and its general handling qualities. In this study only the lift-drag performance is of interest; however, the times and costs reflect the total job.

  To carry out a wind-tunnel test, it is necessary to plan the test(s), build the model, obtain the use of a wind tunnel, run the test(s), and analyze the data.
- *Wind Tunnel: Small Aircraft*. The wind-tunnel testing of a small model of the aircraft uses a model with a 5-ft wing span.

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*The reader is referred to Alan Pope, *Wind-Tunnel Testing*, 2d ed., John Wiley & Sons, Inc., New York, 1954, for a thorough explanation of wind-tunnel testing.

The time, cost, and precision figures are: time equals 5 weeks; cost equals \$160,000; and precision equals 10 percent. Information obtained is for the frictional drag coefficient of the aircraft, C_{D_f}, and the airplane efficiency factor, e.

- *Wind Tunnel: Large Aircraft.* The model used in this test has a wing span of approximately 10 feet. The model has remotely operable flaps, landing gear, control surfaces, bomb bays and electrically driven propellers. The test provides information about C_{D_f} and e. The time required is 20 weeks, the cost is \$3 million, and the precision is 7 percent.
- *Wind Tunnel: Large Wing.* The model used in this test has a span (single wing) of 20 feet. The information obtained is for C_{D_f} and e of the wing. The time required is 10 weeks, the cost is \$500,000, and the precision is 3 percent.
- *Wind Tunnel: Large Fuselage.* The model has a height of 6 feet and a stub-wing span of 20 feet. The information obtained is for C_{D_f} of the fuselage and tail. The time required is 10 weeks, the cost is \$500,000, and the precision is 3 percent.
- *Assemble and Test.* A complete testing program requires construction of three aircraft: one is for static test and two are for flight test. In the present study, the results of assemble and test are a value for the gross take-off weight, a value for the frictional drag coefficient of the aircraft, and a value for the airplane efficiency factor. The latter two figures are used to compute the fuel economy figure. The time for assemble and test is 52 weeks, the cost is \$300 million, and the results are perfect--no uncertainty remains.*
- *Deliver.* The terminal action requires only a minimum amount of paper work. The customer usually sends a crew to pick up the airplane. The time is 1 week, and the cost is \$1000. A precision figure does not apply. The terminal action is concerned

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*In reality, there will always be some residual uncertainty. However, the results obtained in this study are not compromised by this assumption. The only thing affected by this assumption is the testing procedure(s) to determine the system performance values to be used in the incentive contract, and the procedure is not made explicit in this study.

only with time and cost, since all performance characteristics have been determined under assemble and test.

STATE OF KNOWLEDGE: TECHNOLOGY

At any given time there is a state of knowledge regarding the system being developed. This knowledge may be classified into two categories: information regarding values of the characteristics of the system and its parts and the relationships between the characteristics. Information regarding the characteristics will be discussed in the next section.

The relationships between the characteristics are a body of scientific or technical knowledge--termed here a "technology." As an example, the weight of an aircraft must be the sum of the weights of everything that goes into it. Similarly, but not as simply, the overall performance of the aircraft is influenced by the performance of the engines and the aerodynamic characteristics of the airframe. These relationships form a hierarchy as shown in Fig. 4.

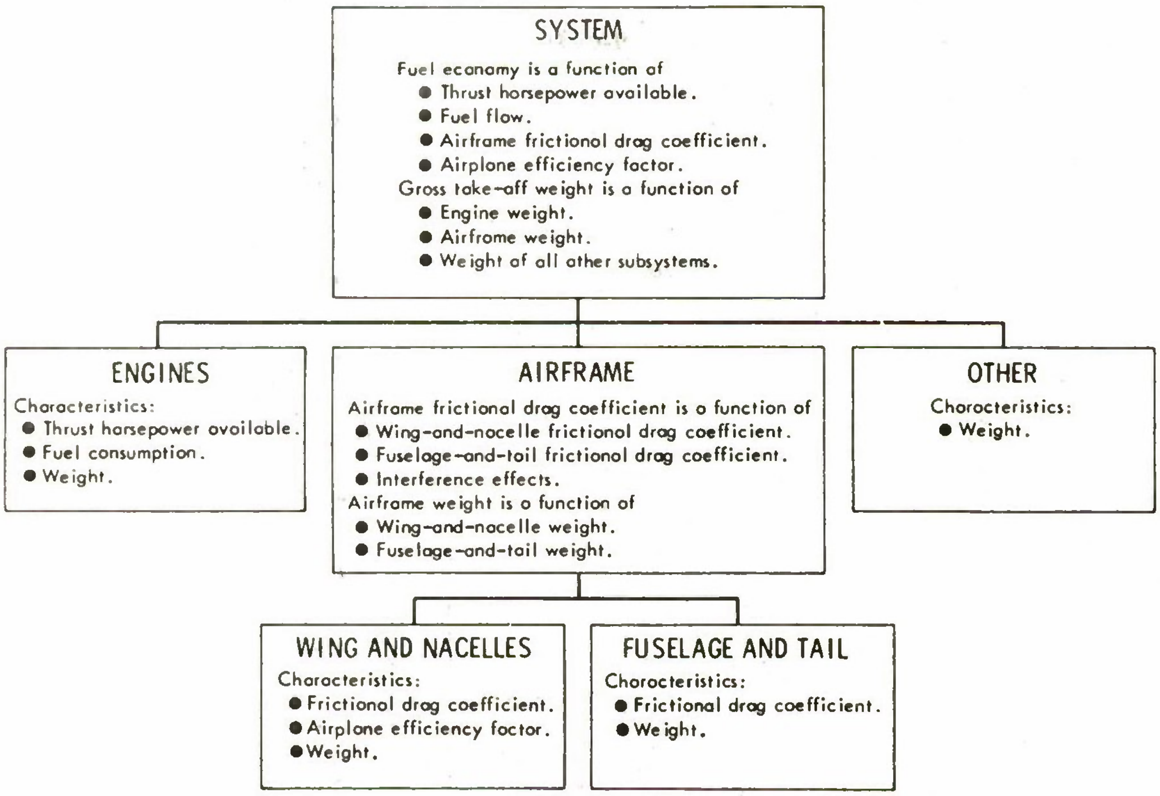

Fig. 4--Hierarchy of design equations and inputs

A given system development project is concerned with a given technology or group of technologies. Development of a turbine-engine aircraft is concerned with the technologies of turbine engines and aerodynamics.

To be amenable to the present research, the technologies must be represented mathematically--by analytical functions, graphs, or tables (see Fig. 5). It is not necessary that these representations be exact; however, in the present research they will be considered to be so.*

$$\text{Equation:} \quad C_D = C_{D_f} + \frac{C_L^2}{\pi \mathit{AR}\, e}$$

C_{D_f} = functional drag coefficient = .0250

AR = aspect ratio = 7

e = airplane efficiency factor = .88

Table:

C_D	C_L^2
.0250	0.00
.0290	0.20
.0330	0.40
.0370	0.60
.0410	0.80
.0450	1.00

Graph:

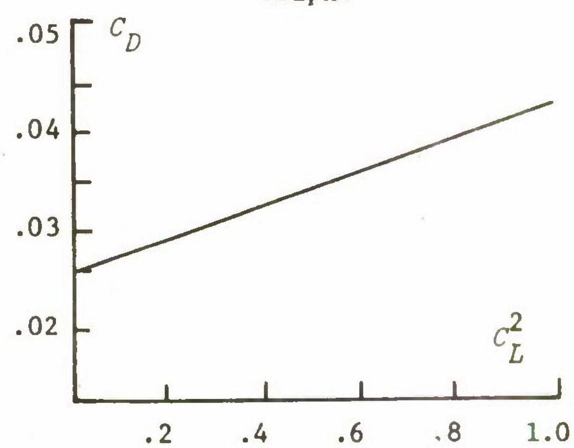

Fig. 5--Alternative forms of presenting the relation between the lift coefficient, C_L, and the drag coefficient, C_D, for a "typical" aircraft

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*An interesting area for further research is concerned specifically with uncertainty about the functional forms of technology--call it scientific uncertainty. See the discussion in Sec. VII, under "Extensions."

Furthermore, in the present research, only analytical functions will be used; tables or graphs could be used just as effectively but probably not as efficiently because the memory (core) requirement for the tables is very large. The analytical functions are the design equations referred to previously.

For the hypothetical development project the equations are concerned with weight and aerodynamic characteristics. The fuel economy performance of the aircraft is the result of the combined aerodynamic performance of the aircraft and the performance of the engines. The gross take-off weight is the simple sum of the weight of all parts of the aircraft. Derivation of the fuel economy equations is presented in Appendix A.

STATE OF KNOWLEDGE: HIERARCHY OF UNCERTAINTY

The state of knowledge regarding the values of the system and component characteristics at any given time can be represented by probability distributions. The uncertainty regarding the system characteristics (the aggregate technological uncertainty) is related by the design equations to the uncertainty regarding the component characteristics. Hence, there is a hierarchy of uncertainty as shown in Fig. 6.

The distributions at the bottom levels represent knowledge gained by performing engineering tasks such as stress analyses, wind-tunnel tests, weight estimates, etc. The dispersion of these distributions depends on the precision associated with the particular task. For example, a weight estimate by a qualified engineer may be good to plus or minus 10 percent, while the weight determination derived from a complete structural stress analysis may be good to plus or minus 2 percent. The distributions at the intermediate and top levels represent the uncertainty propagated from the bottom level.

Two methods can be used to determine the aggregate uncertainty for any given situation: Monte Carlo Simulation and the Propagation of Error. These two techniques have different characteristics, and the problem of deciding which to use in any given situation is discussed in Appendix D. For the example used in the present research, the means

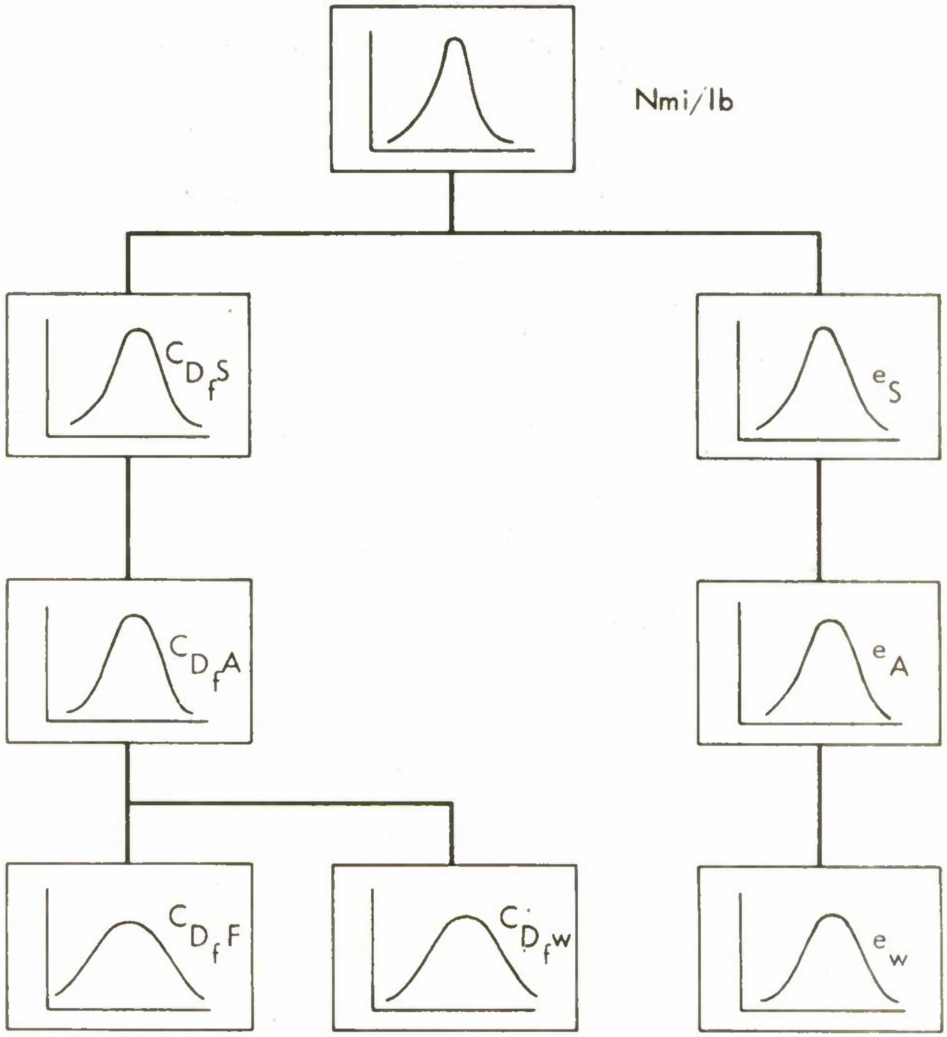

Fig. 6--Hierarchy of uncertainty

and standard deviations obtained from the two methods are reasonably close. Therefore, because propagation of error requires much less computer time and because the purposes of this study require many computer runs, the propagation of error technique was favored for use in this study. This technique requires that the design equations be expressed in analytical form.

For the hypothetical development project, there are eight different hierarchies. Figure 7 shows the initial hierarchies for all eight system configurations. The figures at the lowest level of each branch

	Systems							
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
Combination	E_AA_A	E_AA_B	E_AA_C	E_AA_D	E_BA_A	E_BA_B	E_BA_C	E_BA_D
[illegible]/lb	.0810±.0041	.0852±.0084	.0776±.0062	.0807±.0091	.0965±.0053	.1019±.0110	.0921±.0079	.0961±.0118
[illegible] WT	128000±2546	130500±4080	128900±3049	131900±4427	129500±2546	132000±4080	130400±3049	133400±4427
[illegible]	.024±.0023	.024±.0051	.024±.0036	.024±.0051	.024±.0023	.024±.0051	.024±.0036	.024±.0051
[illegible]	.9±.09	.9±.09	.9±.09	.9±.09	.9±.09	.9±.09	.9±.09	.9±.09

	Engines	
	E_A	E_B
k_0	-5508.22	-5700.0
k_1	4.1126	3.8
k_2	-5.865×10^{-5}	-6.0×10^{-5}
[illegible]	-1924.573	-1900.0
[illegible]	-.01359	-.012
[illegible]	4.43631	4.0
[illegible]	-.0053	-.005
W	1875.0	2250.0

	Airframes			
	A_A	A_B	A_C	A_D
C_{D_f}	.024±.0023	.024±.0051	.024±.0036	.024±.0051
e	.9±.09	.9±.09	.9±.09	.9±.09
W	20500±2546	23000±4080	21400±3049	24400±4427

	Other
	O_A
W	100000

	Wings and Nacelles			
	W_A	W_B	W_C	W_D
S	1300	1300	1600	1600
A	7.5	9.0	7.5	9.0
C_{D_f}	.016±.0016	.016±.0048	.016±.0032	.016±.0048
e	.9±.09	.9±.09	.9±.09	.9±.09
W	8500±850	11000±3300	9400±1880	12400±3720

	Fuselage and Tail
	F_A
C_{D_f}	.008±.0016
W	12000±2400

Fig. 7--Initial hierarchy of uncertainty

were specified first.* Then the figures at higher levels were determined using the design equations relating the characteristics at adjacent levels and the propagation of error technique.

The characteristics that describe an engine are the coefficients and constant terms of equations that are developed in Appendix A. Engine alternative E_A was determined using the T56-A-10W/WA Model

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*The mean values were obtained by using the P-3 aircraft and T-56-A-10W engine data and generating alternatives based on suggestions by personnel at The Rand Corporation and Lockheed California Company. The standard deviations were based on estimates from the same people.

Specification. To insure that there would be a trade-off between engine E_A and engine E_B, the second engine was selected to offer better fuel economy but at a higher weight. The values for engine E_B were determined by increasing the weight above the weight of E_A and then testing the effect of small changes in the coefficients and constant terms just mentioned until an interesting set of numbers was found.*

The characteristics that describe the fuselage and tail are approximate figures for the Lockheed P-3A Orion Aircraft.†

The characteristics that describe alternative wing design W_A are also approximate figures for the P-3A.‡ The other wings were determined by varying the wing area, S, and the aspect ratio, $\mathcal{R}$, from the nominal P-3A.**

The items in the "Other" category contribute only weight from the point of view of the present study. The weight figure used is approximately the weight of the "Other" items for the P-3A.

The initial uncertainties were established by considering what might be reasonable and how much would be interesting. Several test runs of the program were made with different initial uncertainties before the values shown in Fig. 7 were adopted.

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*Initially, all engine parameter values were changed by the same percentage. This resulted in such a drastic change in the fuel economy performance that the method of small perturbations was used.

†Personal communications from E.C.B. Danforth and D. Beier of Lockheed California Company.

‡Ibid.

**Mr. Danforth (see previous footnotes) suggested that optimization of the aircraft design with respect to fuel economy would probably result in the selection of a higher aspect ratio wing; hence, the direction of change. Of course, the P-3A did not have a higher aspect ratio wing, but there were other trade-offs involved in the P-3 development. Furthermore, that development was unique in that the airframe had already been developed and produced as a commercial airliner--the Electra. Consequently, very few, if any, comparisons can be made between the P-3 development and this study. The P-3 was used here to insure that the aircraft's characteristics were consistent and realistic. For a brief account of the P-3 development, the reader should consult *Jane's All The World's Aircraft*, Sampson Low Marston & Co., Ltd., London. The account in the 1963-1964 edition is the most complete regarding the early development.

The initial uncertainties regarding the fuel economy and the gross take-off weight are shown in Fig. 8. The diagonal lines in Fig. 8 are the zero performance incentive payoff lines. The vertical and horizontal dashed lines divide the technical performance plane into four quadrants labeled I, II, III, and IV. The origin of this division is at the zero-incentive performance values: .088 n mi/lb and 130,000 lb. Outcomes in quadrant IV are superior to both zero-incentive values. Fuel economy is higher and gross take-off weight is lower. In quadrant I, the aircraft is overweight but the fuel economy is superior to the zero-incentive value. In quadrant III, the aircraft is inferior to the zero-incentive fuel economy value, but it is underweight. In quadrant II, the aircraft is inferior with regard to both characteristics.

The probability density functions for the initial fuel economy uncertainties and the initial gross take-off weight uncertainties are shown in Figs. 9 and 10, respectively.

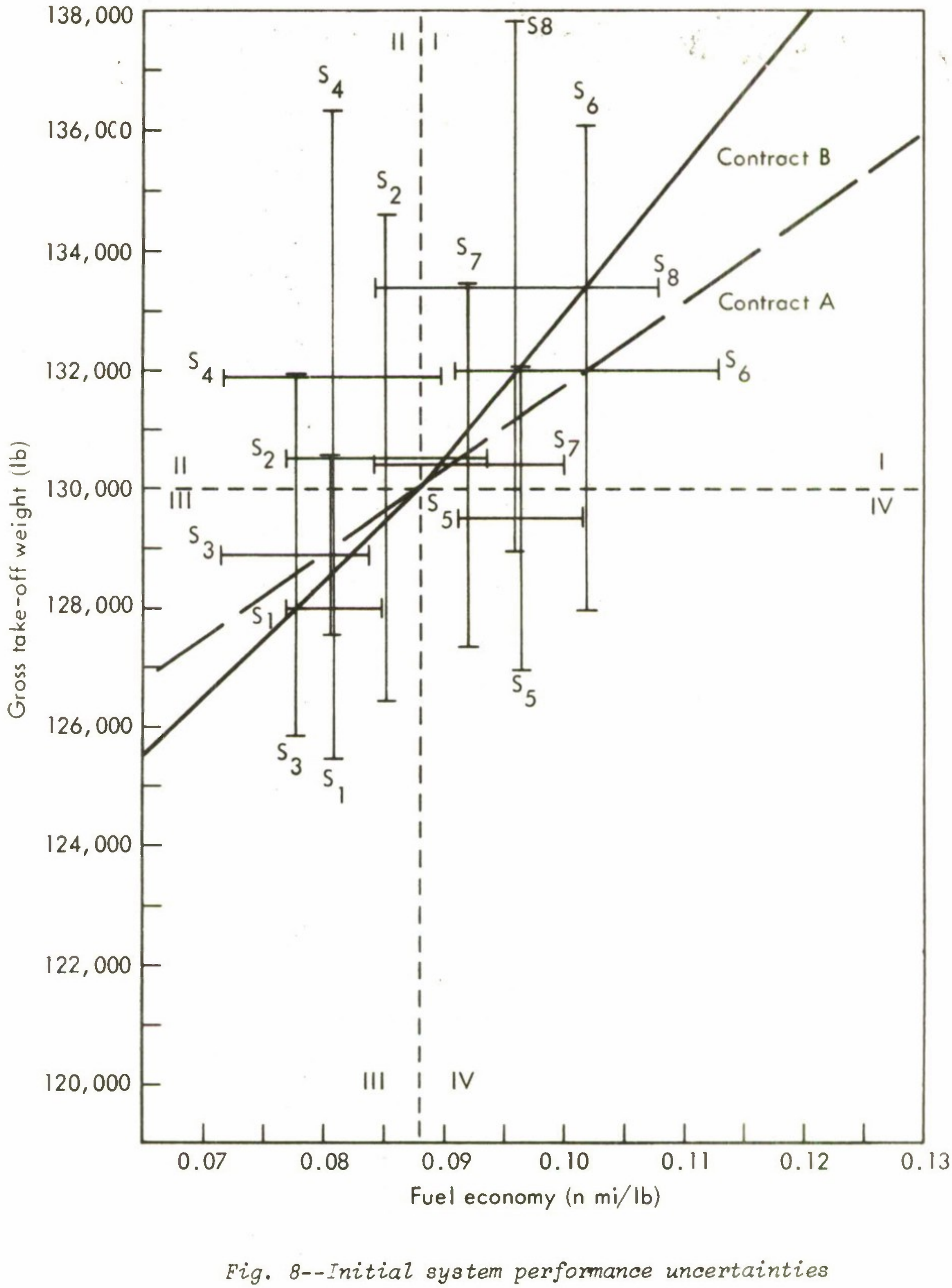

Fig. 8--Initial system performance uncertainties

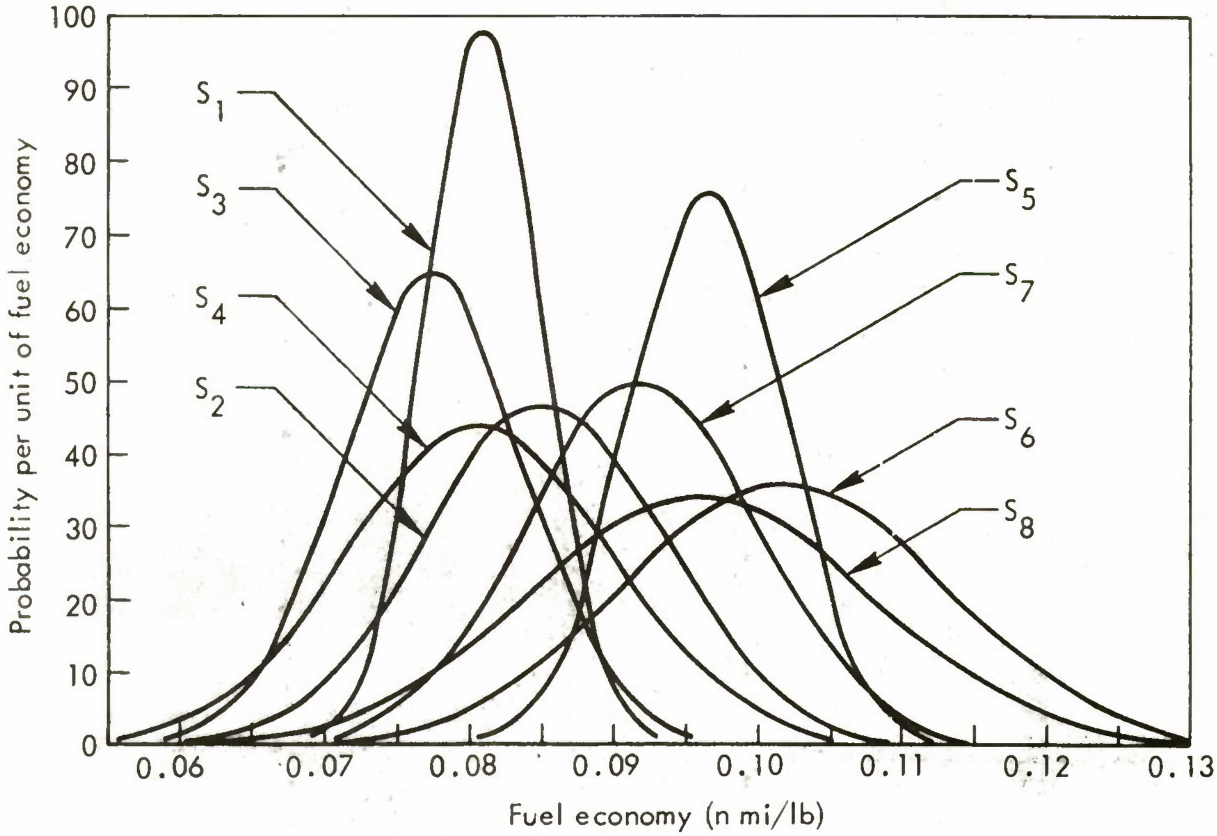

Fig. 9--Initial fuel economy uncertainties

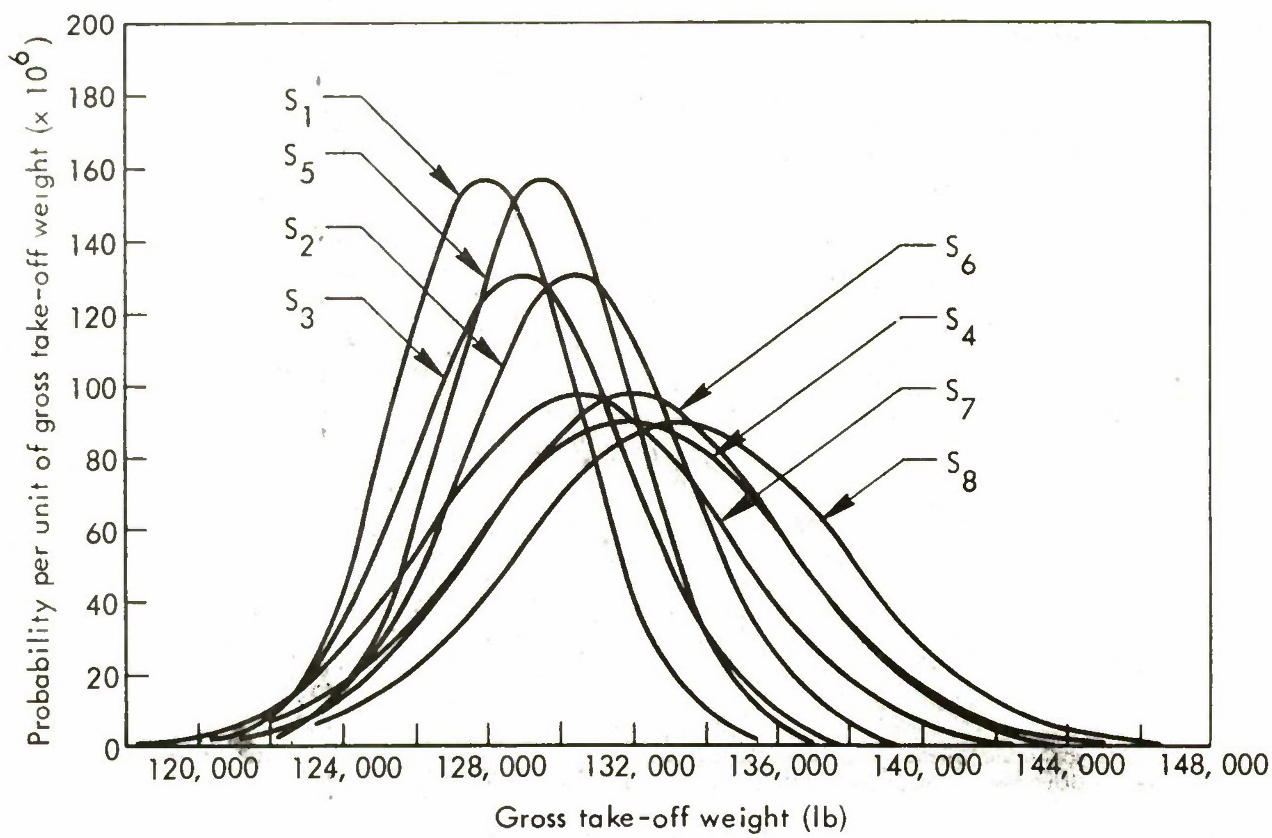

Fig. 10--Initial gross take-off weight uncertainties

III. THE MANAGEMENT CONSIDERATIONS IN A SYSTEM DEVELOPMENT PROJECT: A SIMULATION MODEL OF SYSTEM DEVELOPMENT DECISIONMAKING

GENERAL

At various times during the course of a system development project, a decision must be made about what to do next. These decisions and policies for making them are the main focus of this work. The following is a rough description of the activities and events involved:

1. A decision is made about what to do next.
2. The activity is carried out.
3. Information resulting from the activities become available.
4. The consequences of the information are determined.
5. A decision is made.

:

etc.

A generalized model of this process is shown in Fig. 11. This diagram represents the major decision and information functions of the process of system development. The only real difference between the diagram and the actual computer program used in this study is that the bookkeeping functions are not represented in the diagram. The discussion in this section will proceed using Fig. 11 as an outline. A more detailed description of the program is contained in Appendix C.

INITIALIZATION

Evaluation of alternative decisionmaking policies by repeated simulation of the decisionmaking process requires that each time the process is begun, the conditions must be the same. In the present research, the initial conditions of importance are the initial state of knowledge--both the technology and the initial distributions for the characteristics of the system and its parts--and the characteristics of the actions.

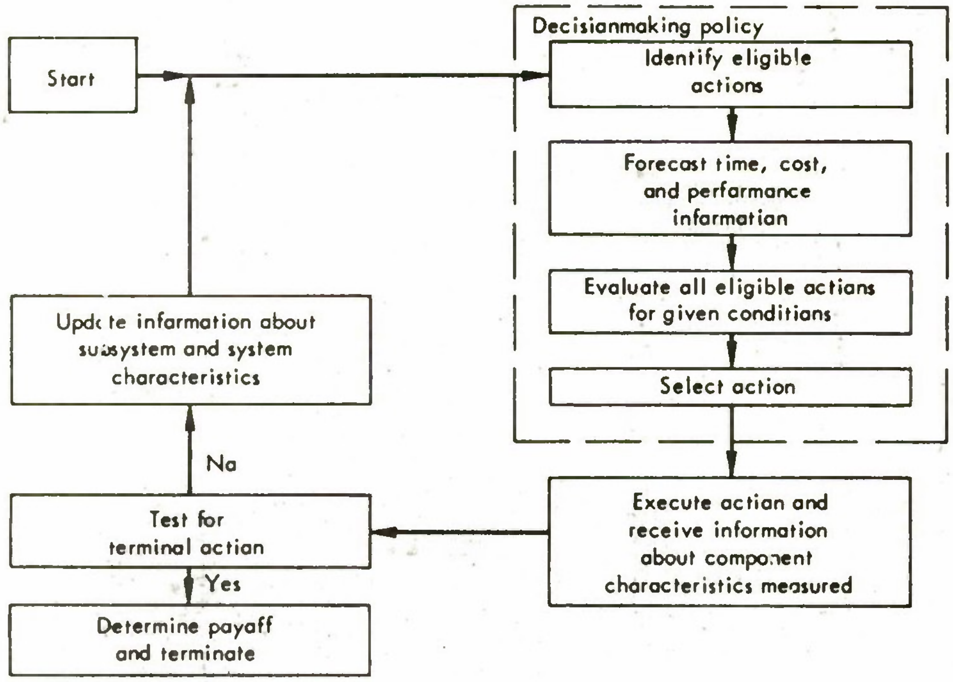

Fig. 11--General model of system development decision and information elements

In the present research, the technology and the characteristics of the actions remain constant.* The technology is represented by the design equations. The characteristics of the actions are read in as data and can be changed with no reprogramming.

The distributions for the component and system characteristics change when actions are executed.† Hence, they must be restored to their initial values each time a new simulation is begun.

DECISIONMAKING POLICY

A decisionmaking policy consists of operations that identify eligible actions; forecast the time, cost, and performance information to be

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*For future use, it would be desirable to relate the times and costs of the actions to the characteristics of the component or subsystem involved in the actions. See section on refinements in Sec. VII.

†The author's previous work on measuring progress in system development is concerned with such changes in probability distributions. See Timson, op. cit.

used in evaluation; evaluate actions using the forecasts; select the action that maximizes or minimizes the evaluation criterion; and execute that action. These operations will be discussed in general terms immediately below. Specific details of the policies studied in this research are presented in Sec. IV.

Eligibility

As was mentioned in Sec. I, eligibility is related to scheduling. Scheduling analysis developed in production management and was concerned with questions of the logical sequencing of actions and the availability of and location of resources required to execute the actions.

In system development, and any other process that involves learning, another sequencing consideration becomes important. This can be phrased as a question: Are there any actions with particular characteristics that should be executed at some particular decision point or in a particular sequence? This consideration is concerned with whether there are actions that can obtain some particularly useful information early in the program, or that can obtain some information at very low cost and in a very short time, or that can obtain information that will be more useful when additional information is available. An example of such a consideration is to perform all actions that quickly and cheaply will yield information on many alternative designs or approaches.*

In the present research, the sequences of actions is due more to the step-by-step evaluation and selection of actions than to any predetermined scheduling; hence, the term "eligibility" is used to identify the sequencing or scheduling aspects of the process. At each decision point, all actions are screened to see if they satisfy the sequencing considerations. Those actions that do are said to be "eligible" for selection. These actions are evaluated after information regarding their characteristics and the present state of knowledge regarding the project are subjected to a forecast, as described next.

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*This corresponds to one of the "rules of a good development policy" prescribed by Klein, op. cit., pp. 4-5.

Forecast Information

Given a list of eligible actions to evaluate, it is necessary to have the information to be used in the evaluation and a rule for processing the information. The model of system development used here contains a number of items that can be used in the evaluation. These are as follows:

- o The state of knowledge, which may be the present state or a lagged state.*
- o The characteristics of the actions, including times, costs, and precision of new knowledge.
- o The time and money consumed.

Any combination of these items may be used.

In general, the evaluation rule will be based on some forecasted values for the items considered. The available information regarding the items can be processed in a number of ways to obtain different forecasts of the outcomes that will result from actions. Consequently, the methods of forecasting will influence the decisions that are made. In the present study, four policies have been examined that consider time, cost and performance, and one policy that considers performance only.

Time and Cost Forecasts. Forecasting time and cost may be based on many factors. In this study, one forecasting procedure is used in all policies that require a forecast of time and cost. The procedure makes a forecast of the minimum number of actions required to complete the project as imposed by the eligibility rule. It does not reflect uncertainty. Details of the procedure are described in Sec. IV.

Performance Forecasts. Information regarding technical performance for use in evaluation may also be determined in a number of

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*Time lags may affect all information or only certain items of information. Examination of different lags and different patterns of lags gives some indication of the value of different communication patterns in a system development organization.

different ways. Before discussing the procedures used in this study, some terms must be defined to identify the probability distributions at various times.[*] The probability distribution available before an information-buying action is taken is called the prior probability distribution, or simply the prior. The prior specifies the distribution of outcomes that would be expected if a terminal action was to be taken. The probability distribution available after the action is taken and the new information is learned is the posterior probability distribution, or simply the posterior. Before the information-buying action is taken, a forecast can be made of the distribution of the mean of the posterior if the sample variance is known. This distribution is known as the prior distribution of the posterior mean, or simply the preposterior. The preposterior specifies the distribution of outcomes that would be expected if the information-buying action was to be taken, the new information learned, and the terminal action taken.

Three performance forecasting schemes are included in the policies considered in this study. The simplest scheme sets the mean of the forecast distribution equal to the prior mean and the standard deviation of the forecast equal to zero; i.e., the prior mean is used as a certainty equivalent. Because the probability distributions in this study are all assumed to be normal, the preposterior mean is equal to the prior mean;[†] hence, the forecast is just the preposterior mean.

A second forecasting scheme uses the complete preposterior analysis.[‡] For any given action, the precision of the new assessment (after the action) is known. This precision is related to the sampling variance. To determine the preposterior distributions for characteristics at the system level, first identify the component characteristics whose estimated values will be refined by the action being evaluated. Then determine the preposterior distribution for those characteristics. Next, using the preposterior for the characteristics whose estimated

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[*] The terminology is that used in common practice. See, for example, Robert Schlaifer, *Probability and Statistics for Business Decisions*, McGraw-Hill, New York, 1959. See especially p. 337 and Chap. 33.

[†] Ibid., pp. 525-528.

[‡] Loc. cit.

values will be refined and the priors for all other (non-refined) characteristics, determine the preposteriors for higher level characteristics using the updating procedures described below. This provides a forecast in the form of a distribution of outcomes that may result from a given action.

The third forecasting scheme considered in this study uses the preposteriors for the characteristics measured by a given action. Forecasts for higher levels are made by applying the updating procedures using these preposteriors and the initial prior means for the characteristics not affected by the action. The other characteristics are represented by the means of the initial prior distributions for the particular design that was the best at the beginning of the project as if no new information was communicated during the project.

Comparing results obtained using the first scheme with results using the second scheme gives an indication of the value of doing a complete preposterior analysis using all available information concerning uncertainty as compared to using only the means. Comparing results obtained using the second scheme with results using the third scheme gives an indication of the value of using information currently available for all decisions as opposed to using "old" (unrevised) information regarding all items except those concerned with the immediate action.

EVALUATION AND SELECTION RULES

An evaluation rule is a rule that prescribes how the information that results from the forecast will be combined to arrive at a number that indicates the value of carrying out an action.

In this study, two evaluation rules are used. The first is an approximation* to the "standard" prescription of normative decision theory--

*The rule is called an approximation so the reader will not be misled into thinking that the decisionmaking policies used in this study are on the same basis as the expected payoff calculations found in sequential decision theory. The fundamental difference is that sequential decision theory involves only one kind of information-buying action, while the present work is concerned with several types of information buying actions. The present situation is further complicated by the requirement that a certain number of information-buying actions be executed before a terminal action is permitted (called the "eligibility rule" here). The calculations in sequential decision theory calculate the expected payoff for each eligible action and select that action that maximizes the expected payoff. The payoff is determined by the multiple incentive contract; and because the system performance characteristics are represented by probability distributions, the payoff must also be represented by a probability distribution. Utility for money is not considered in this study.

The second rule is to calculate the probability of technical success for each eligible action and select that action that maximizes the probability of technical success. The probability of technical success is defined as the probability that the system will meet or exceed the zero-incentive levels of all system performance characteristics contained in the incentive contract.

EXECUTION AND RECEIPT OF INFORMATION

Once an action has been selected, execution is represented by a simple random process that determines the new state of knowledge. In addition, many bookkeeping activities are performed. Execution of the action results, in the real world, in the consumption of some resources, the passing of some time, and the gaining of some knowledge. In the simulation model, the consumption of resources is represented by incurring the cost associated with the action; the passing of time is represented by the time associated with the action; and the gaining of knowledge, for the characteristics measured by the action, is determined by drawing a random sample from the prior distributions. The means of the new distributions are set equal to the sample means from the respective distributions. The standard deviations of the new distributions are set equal to the product of the sample standard deviations associated with the actions times the respective new means.*

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compares the expected value of taking a terminal action with the expected value of an information-buying action followed by a terminal action. In the present work, a terminal action is not always permitted. Furthermore, the fact that several actions may be required by the eligibility rule before the terminal action is permitted makes it a difficult task to examine all permutations and combinations of actions required to reach a terminal decision. Thus, the evaluation step is based on comparing individual information-buying actions followed by a terminal action, whether this is feasible or not. Terminal actions enter the evaluation only when they are "eligible."

*An alternative method of revising probability distributions in the light of new information is the "Bayesian" method. See Schlaifer, op. cit., Chap. 21.

The bookkeeping requirements are the following:

1. Identify the selected action by the present step number.
2. Increase the step number by one.
3. Eliminate the selected action from future consideration.
4. Eliminate any actions preempted by the choice from future consideration.
5. Record any prerequisites satisfied by having done the selected action.

TEST FOR TERMINAL ACTION

The test for selection of a terminal action is only one of the many branching points in the whole program. The only reason it is shown in Fig. 11 is because it leads to termination of the process.

UPDATING SUPERIOR QUANTITIES

If the action selected is not a terminal action, then the component and system characteristics that are superior to those measured must be revised in the light of the new information.

Updating superior quantities is the term for the process of determining the probability of distributions of more aggregate (superior) quantities given the distributions for less aggregate (subordinate) quantities and the relationships between the quantities. The process is required at two different places in the simulation model. First, it is used after information is received from an action. In this case, the characteristics measured by the action must be identified. Then the characteristics that are superior (more aggregate) are (re)determined using the new distributions for the characteristics measured and the "old" distributions for all the other characteristics. The second place requiring updating was mentioned above--when determining superior preposteriors. The process is identical in both cases.

Updating, or aggregating, can be accomplished using either Monte Carlo methods or the Propagation of Error. These techniques and methods for choosing between them are discussed in Appendix D. The details of updating through the hierarchy of components for the example used in the study are contained in Appendix C.

TERMINATION AND OUTPUT

If the action selected was a terminal action--that is, deliver the system--then the output items must be recorded. The items selected for output in this study are:

- o The sequence of actions selected.
- o The characteristics of the system that was delivered.
- o The alternative design that was delivered.
- o The incentive contract payoff.
- o The time and cost (not including payoff) of the project.

These items constitute a history of the development project. The computer program is capable of generating any number of project histories by re-establishing the initial conditions. Figure 11 illustrates the process for generating an individual project history.

IV. DECISIONMAKING POLICIES CONSIDERED

The decisionmaking policies examined in this research are organization oriented. The criteria for decisionmaking used in the policies are the system performance characteristics, the program cost and time, and the incentive fee. These criteria are of primary importance to the organization but, perhaps, of less importance to the individuals within the organization.

During the course of this research, nine different decision policies were considered. Five of these policies were selected for study using samples of 51 runs each. The characteristics of the policies are summarized in a table later in this section.

POLICY 1: MAXIMIZE EXPECTED PAYOFF

Summary of Policy Characteristics

Policy 1 is a surrogate for the usual analysis of a choice between taking a terminal action or taking an uncertainty reducing action.* The usual decisionmaking analysis uses preposterior probability distributions and expected value calculations. It proceeds as follows: (1) Calculate the net expected value for a terminal action, EV_t, using the prior distributions of possible outcomes.† (2) Calculate the net expected value for an uncertainty reducing action followed by a terminal action, EV_s, using the preposterior distributions of possible outcomes. (3) If EV_s is greater than EV_t, then select the uncertainty reducing action, otherwise select the terminal action. An equivalent form of this rule is to calculate the difference $EVI_s = EV_s - EV_t$ and select the uncertainty reducing action if the difference is positive, otherwise select the terminal action. In the case of n different uncertainty reducing actions, the quantities $EVI_i = EV_i - EV_t$, are calculated for all actions $i = 1, \ldots, n$. If EVI_i is positive for at least one action, then select the action that has a maximum value of EVI, otherwise select the terminal action.

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*See Schlaifer, op. cit. Chap. 33.

†Details of this calculation vary from policy to policy. Explanations of these variations are given throughout this section.

Policy 1 differs from the "usual" procedure just described with respect to the means of calculating the EV quantities. Policy 1 calculates the net expected payoff for an information buying action followed by a minimum sequence of actions required to reach a terminal state. The preposterior analysis is carried out for the characteristics that will be measured by the action being evaluated. The times and costs of the actions in the minimum sequence are included in the calculation, but the information to be gained from these actions is omitted. Denote the quantities obtained using this procedure by $EV1_i$, $i = 1, \ldots, n$.

There is another difference between Policy 1 and the "usual" procedure. The eligibility rule requires that certain actions be executed before a terminal action becomes eligible for selection. When the prerequisites are all satisfied, the expected payoff of the eligible terminal action, EV_t, is included with the $EV1_i$ values and the action having the maximum value is selected. The same result is obtained by selecting the action that maximizes the quantity $EVI1_i = EV1_i - EV_t$, if $EVI1$ is positive for at least one action, and selecting the terminal action otherwise. This is the same as the "usual" procedure. The difference occurs when the prerequisites are not satisfied and a terminal action is not eligible. In this case, the action that maximizes $EV1$ is selected, but EV_t does not enter into the selection. However, there is still a strong similarity between the procedure of Policy 1 in this case and the "usual" procedure. There is a value for EV_t at each decision point whether or not a terminal action is eligible. Denote the value of EV_t at a decision point where a terminal action is not eligible by EV_t'. Selecting the action that maximizes $EV1_i$ at such a decision point is equivalent to selecting the action that maximizes $EV1_i - EV_t'$ regardless of the sign of the difference.

Of all the policies considered in this research, Policy 1 is about the closest approximation to the "usual" procedure. Consequently, it is labeled "maximize expected payoff."

Eligibility Rule

A minimum of one action must be selected from each of the ten activity categories. An assemble and test must be done before a deliver may be selected, and one action from each of the eight experiment activities must be done before an assemble and test may be selected. Hence, a project history will contain at least one action from each of the ten categories shown in Table 2. This rule is reasonable because each of the activities generates certain output that is necessary for fabrication and assembly of the system. For example, the wind tunnel tests will determine the shape of the exterior of the aircraft and the stress analysis creates the drawings of how the internal and external structures will be put together. The rule is not reasonable in that it does not require that each of the ten activities be directed at the same system design.

Forecasting Time and Cost

Time and cost forecasts are based on action forecasts. The action forecast is based on the eligibility rule. The basic forecast is that one action will be selected from each activity category that has not yet had an action selected from it. Because of the mechanism for keeping track of the eligibility requirements, there are two variations in the details of the calculations. In the first variation, the action being evaluated *will* be the first chosen from its category--the eligibility consideration for this has *not* been previously satisfied. In this case, the basic forecast already includes the action being evaluated. In the second variation, the action being evaluated will *not* be the first chosen from its category--the eligibility consideration for this category *has* been previously satisfied. In this case, the basic forecast does not include the action being evaluated. The two cases can be expressed as

$$\left.\begin{aligned} TA &= TP + TU \\ CA &= CP + CU \end{aligned}\right\} \quad \text{Case I,} \qquad (7)$$

$$\left.\begin{aligned} TA &= TP + TU + TE \\ CA &= CP + CU + CE \end{aligned}\right\} \quad \text{Case II,} \qquad (8)$$

where *TA* is the forecast time, *CA* is the forecast cost, *TP* is the accumulated time of all actions that have been selected, *CP* is the accumulated cost of all actions that have been selected, *TU* is the sum of the times of one action from each activity category from which no action has yet been selected, *CU* is the sum of the costs of one action from each activity category from which no action has yet been selected, *TE* is the time of the action being evaluated, and *CE* is the cost of the action being evaluated.

Forecasting Performance

The evaluation rule described below uses probability distributions for the two system performance characteristics that appear in the multiple incentive contract. To obtain a forecast of these distributions, the characteristics that are measured by the action to be evaluated must be determined first. Next, using the precision of the action, the preposterior distributions for the characteristics measured are established. Then, the propagation of error technique is used to determine the preposterior distributions for the system characteristics. The preposterior distribution for characteristic c_i measured by action a_j is determined from*

$$E(E_{pp}(c_i)) = E_p(c_i), \tag{9}$$

$$\sigma(E_{pp}(c_i)) = \sigma_p(c_i) \left[\frac{\sigma_p^2(c_i)}{\sigma_p^2(c_i) + \sigma_j^2(c_i)} \right]^{\frac{1}{2}}, \tag{10}$$

where $E(\quad)$ indicates the mean of the argument, $\sigma(\quad)$ indicates the standard deviation of the argument, the subscript *pp* identifies a preposterior quantity, the subscript *p* identifies a prior quantity, and the subscript *j* identifies a sample quantity--e.g., a quantity determined by an information buying action. The precision of each activity is expressed by the coefficient of variation; hence, the sample standard deviation equals the coefficient of variation times the mean. Consider the wind tunnel test for the fuselage and tail, action number 42 as

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*These expressions are for the case of a normal prior and sampling distributions with known sampling variance. See Schlaiffer, op. cit., Chap. 34.

shown in Table 2. The characteristic measured is the drag coefficient for the fuselage and tail, $C_{D_f F}$. Suppose that the prior distribution for $C_{D_f F}$ has a mean of .008 and a standard deviation of .0008. The precision of the activity is shown in Table 2 to be 3 percent. Hence, the sample standard deviation is

$$\sigma_{42}(C_{D_f F}) = .03 \times .008 = .00024. \tag{11}$$

The preposterior distribution is thus

$$E(E_{pp}(C_{D_f F})) = E_p(C_{D_f F}) = .008. \tag{12}$$

$$\sigma(E_{pp}(C_{D_f F})) = .0008 \left[\frac{(.0008)^2}{(.0008)^2 + (.00024)^2} \right]^{\frac{1}{2}}$$

$$\simeq .00076. \tag{13}$$

The preposterior distributions for the system performance characteristics are determined using the prior distributions for the component characteristics that are not measured and the preposterior distributions for the component characteristics that are measured. For the example above, the preposterior for the gross take-off weight is the same as the prior because the action being evaluated does not produce information about weight.

To demonstrate how the propagation of error technique is used to determine the preposterior for the nautical miles per pound of the aircraft, consider the following case. The action being evaluated is action number 42, as above. The system design for which the preposterior is to be determined is design S_1. As shown in Fig. 7, this system design consists of engine design E_A and airframe design A_A; and aircraft design A_A consists of wing design w_A and fuselage design F_A. Suppose that the present state of knowledge for the drag coefficient of wing design w_A is $E(C_{D_f w_A}) = .016$, $\sigma(C_{D_f w_A}) = .00016$, $E(e_{w_A}) = .9$, and $\sigma(e_{w_A}) = .09$. Then, using Eqs. (88), (89), (91) and (92), the preposteriors for the aerodynamic characteristics of the airframe are given by

$$E_{pp}(C_{D_f A_A}) = .016 + .008 = .024, \tag{14}$$

$$\sigma_{pp}(C_{D_f A_A}) = [(.0016)^2 + (.00076)^2]^{\frac{1}{2}} = .001771, \tag{15}$$

$$E_{pp}(e_{A_A}) = E_{pp}(e_{w_A}) = .9, \tag{16}$$

$$\sigma_{pp}(e_{A_A}) = \sigma_{pp}(e_{w_A}) = .09. \tag{17}$$

The preposterior for the nautical miles per pound is given by $E_{pp}(NMI/LB)$ and $\sigma_{pp}(NMI/LB)$, determined as indicated in Appendix B.

Evaluation Rule

The value assigned to any action is determined by calculating the expected payoff under the multiple incentive contract. If the action has as its object some component that may be used with a number of different system designs, then the payoff must be determined for each design that uses the component. The highest value is selected as the value of the action.

There are four components to the expected payoff calculations: time, cost, and the two performance incentives. The time and cost payoff are not subject to uncertainty in the present formulation.* The time and cost payoffs are determined using Eqs. (2) and (3) with CA and TA given by Eqs. (7) or (8).

The performance payoffs can be calculated as expectations because the probability distributions for the performance values are available.† The expected payoff for the incentive on nautical miles per pound is given by

$$EPANMI = \frac{\sigma_{pp}}{\sqrt{2\pi}} (RPSNMI - CPSNMI) \exp\left(-\frac{PSRNMI - E_{pp}}{\sigma_{pp}}\right)^2$$

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*Some ideas for changing this are presented in Sec. VII.

†Derivations of these two expressions are contained in Appendix B.

$$+ \ CPSNMI \left(\frac{\sigma_{pp}}{\sqrt{2\pi}} + E_{pp} - PSRNMI \right)$$

$$+ \ \frac{(RPSNMI - CPSNMI)(E_{pp} - PSRNMI)}{2} \ ERFC \left(\frac{PSRNMI - E_{pp}}{\sqrt{2}\ \sigma_{pp}} \right), \tag{18}$$

where σ_{pp} denotes $\sigma_{pp}(NMI/LB)$, E_{pp} denotes $E_{pp}(NMI/LB)$, and *ERFC* is the cumulative error function. All other symbols are as defined in Sec. II.

The expected payoff for the incentive on gross take-off weight is given by

$$EPAGTO = \frac{\sigma_{pp}}{\sqrt{2\pi}} \ (CPSGTO - RPSGTO) \ \exp \left(- \frac{PSRGTO - E_{pp}}{\sigma_{pp}} \right)^2$$

$$- \ RPSGTO \left(\frac{\sigma_{pp}}{2} + E_{pp} - PSRGTO \right)$$

$$+ \ \frac{(RPSGTO - CPSGTO)(PSRGTO - E_{pp})}{2} \ ERFC \left(\frac{PSRGTO - E_{pp}}{\sqrt{2}\ \sigma_{pp}} \right), \tag{19}$$

where σ_{pp} denotes σ_{pp}(GTO WT), and E_{pp} denotes E_{pp}(*GTO WT*), all other symbols are as above.

The expected incentive payoff is given by the sum of the four terms.

Preliminary Results

The results obtained with this policy were sufficiently interesting to warrant its use in large-sample runs. More important is the fact that this policy constitutes the "base case." All other policies represent some kind of deviation from this policy.

It is not necessary to read the rest of this section unless a knowledge of the details of all the policies is required. Table 3, coupled with some of the details of Policy 1, should be sufficient to understand the remainder of the study.

Table 3

SUMMARY OF DECISIONMAKING POLICIES CONSIDERED

#	Name	Eligibility	Forecasts/Information		Evaluation	Preliminary Results
			Time and Cost	Performance		
1	"Maximize Expected Payoff"	One action from each experiment activity must precede assemble and test which must precede deliver.	Present plus uncompleted prerequisites plus action being considered if prerequisite satisfied.	Preposteriors for characteristics measured, priors for all others.	Maximize expected payoff using multiple incentive contract and forecasts.	Reasonable outcomes. Some search beyond minimum action requirements
2	"Straight Expected Payoff"	Assemble and test must precede deliver.	Present plus assemble and test plus deliver.	Same as #1.	Same as 1.	All sequences of actions: assemble and test then deliver.
3	"Expected Payoff Divided by Cost"	Same as #2.	Same as #2.	Same as #1.	Maximize the ratio of expected payoff (as in #1) divided by the cost of the action being evaluated.	If values negative when first assemble is selected, then all assembles selected before delivery.
4	"Current Means Analysis"	Same as #1.	Same as #1.	Use means of priors only.	Same as #1.	Reasonable outcomes. No search beyond required actions.
5	"Low Cost Actions First"	All weight estimates and small wind tunnel tests first, then same as #1.	Same as #1.	Same as #1.	Same as #1.	Reasonable outcomes. Some search beyond minimum action requirements.
6	"Initial Prior Means, Optimistic"	Same as #1.	Same as #1.	Preposteriors for characteristics measured, means of <u>best</u> initial design for all others.	Same as #1.	Extremely long sequences of actions.
7	"Initial Prior Means, Pessimistic"	Same as #1.	Same as #1.	Same as #6 except: <u>worst</u>.	Same as #1.	Same as for Policy No. 6.
8	"Probability of Success"	Same as #1.	Evaluation is not dependent on time or cost.	Same as #1.	Select action that maximizes probability of technical success until delivery is eligible, then deliver regardless of success.	Reasonable outcomes. Search is frequently longer than minimum but not excessively so as with Policies 6 and 7.
9	"No Failures Delivered"	Same as #1.	Same as #8.	Same as #1.	Same as #8 except: do not deliver if system does not meet or exceed requirements.	Complete failure is frequent.

POLICY 2: STRAIGHT EXPECTED PAYOFF

Summary of Policy Characteristics

Policy 2 yields measures that are surrogates for the incremental value of an uncertainty reducing action except that no experiment category actions are required as prerequisites to the assemble and test category actions. The only difference in the evaluation procedure is that the time and cost forecasts are based on a much shorter minimum sequence of actions required to reach a terminal state. Policy 2 is labeled straight expected payoff because the calculation is the same as for Policy 1, but the minimum sequence is much shorter.

Eligibility Rule

The same as for Policy 1 except that none of the experiments are required.

Forecasting Time and Cost

There are three cases. First, if the action being evaluated is a deliver action, then the forecasts are given by

$$\left.\begin{aligned} TA &= TP + TE \\ CA &= CP + CE \end{aligned}\right\} . \tag{20}$$

Second, if the action being evaluated is an assemble and test action then the forecasts are given by

$$\left.\begin{aligned} TA &= TP + TE + T(\mathrm{I}) \\ CA &= CP + CE + C(\mathrm{I}) \end{aligned}\right\} , \tag{21}$$

where $T(\mathrm{I})$ and $C(\mathrm{I})$ are the time and cost for a deliver action. Third, if the action being evaluated is an experiment action, then the forecasts are given by

$$\left.\begin{aligned} TA &= TP + TE + T(\mathrm{II}) + T(\mathrm{I}) \\ CA &= CP + CE + C(\mathrm{II}) + C(\mathrm{I}) \end{aligned}\right\} , \tag{22}$$

where $T(\mathrm{II})$ and $C(\mathrm{II})$ are the time and cost for an assemble and test action.

This forecasting scheme is based on the following action forecast: Whatever action is selected at the present decision point, the subsequent actions will be the minimum required to reach a terminal state.

Forecasting Performance

This is the same as for Policy 1.

Evaluation Rule

This is the same as for Policy 1.

Preliminary Results

All test sequences for this policy produced the same results. The first action selected is an assemble and test and then a deliver. This is not interesting so the policy was not used in large sample runs.

POLICY 3: EXPECTED PAYOFF DIVIDED BY COST

Summary of Policy Characteristics

Policy 3 yields a measure that is similar to a rate of return. The expected payoff calculations using Policy 2 are divided by the cost of the action being evaluated; hence, the measure is the amount of expected payoff per dollar spent.

Eligibility Rule

This is the same as for Policy 2.

Forecasting Time and Cost

This is the same as for Policy 2.

Forecasting Performance

This is the same as for Policy 1.

Evaluation Rule

The evaluation rule is the same as for Policy 1, except that the expected payoff is divided by the cost of the action being evaluated, C_E.

Preliminary Results

Dividing by the cost of the action being evaluated results in high values for low-cost actions and low values for high-cost actions when the expected payoff is positive. However, when the expected payoff is negative, high-cost actions have higher (less negative) values than low-cost actions. As a consequence of the former condition, all the low-cost actions are selected at the beginning of the project; this is not undesirable, but a much simpler policy would produce the same results. The latter condition is disastrous. Whenever the expected payoff becomes negative then all high-cost actions will be selected before the low-cost actions. In the hypothetical project, if the expected payoff turns negative before a deliver action is selected, all assemble and test actions will have higher values than the deliver actions. Consequently, all assemble and test actions will be selected before a deliver action is selected. This happened frequently in the preliminary runs with this policy and it was eliminated from further consideration.

POLICY 4: CURRENT MEANS ANALYSIS

Summary of Policy Characteristics

Policy 4 is intended to show the effect of using a single-valued estimate of the technical outcomes as the basis of the evaluation. The incentive payoff determined by this method may be called the most likely payoff because the means of the system performance distributions are used in the calculation but the standard deviations are not. This type of decisionmaking policy might be used in an organization that did not believe in probability distributions over possible outcomes or one that did not have or could not afford an information processing system that could perform the preposterior analyses and expected value calculations. Policy 4 is labeled current means analysis.

Eligibility Rule

This is the same as for Policy 1.

Forecasting Time and Cost

This is the same as for Policy 1.

Forecasting Performance

This policy ignores the dispersion in the distributions. It uses the means of the distributions as a "best" guess. Hence, the preposterior distributions can be expressed as

$$E_{pp}(NMI/LB) = E_p(NMI/LB), \tag{23}$$

$$\sigma_{pp}(NMI/LB) = 0, \tag{24}$$

$$E_{pp}(GTO\ WT) = E_p(GTO\ WT), \tag{25}$$

$$\sigma_{pp}(GTO\ WT) = 0. \tag{26}$$

Evaluation Rule

The evaluation rule is the same as for Policy 1, except that because the forecast standard deviations are zero, the evaluation expressions reduce to

$$EPANMI = \begin{cases} RPSNMI(PSANMI - PSRNMI), & \text{if} \quad PSANMI \geq PSRNMI \\ -CPSNMI(PSRNMI - PSANMI), & \text{if} \quad PSANMI < PSRNMI \end{cases} \tag{27}$$

and

$$EPAGTO = \begin{cases} RPSGTO(PSRGTO - PSAGTO), & \text{if} \quad PSRGTO \geq PSAGTO \\ -CPSGTO(PSAGTO - PSRGTO), & \text{if} \quad PSRGTO < PSAGTO, \end{cases} \tag{28}$$

where $PSANMI = E_{pp}(NMI/LB)$ and $PSAGTO = E_{pp}(GTO\ WT)$.

Preliminary Results

All project histories were completed in the minimum number of actions required by the eligibility rule. The outcomes were reasonable, and the policy was selected for large-sample investigation.

POLICY 5: LOW-COST ACTIONS FIRST

Summary of Policy Characteristics

Policy 5 is intended to show the effect of examining all the alternative designs early in the development program. This corresponds roughly to Rule 2 of Klein, et al.* This policy differs from Policy 1 only in the eligibility rule that, in this case, requires the low-cost and short-time actions for the four wing and airframe designs to be done first. Policy 5 is labeled low-cost actions first.

Eligibility Rule

The eligibility rule is the same as for Policy 1, except that actions 25-32 and 41 of Table 2 must be executed first.

Forecasting Time and Cost

This is the same as for Policy 1.

Forecasting Performance

This is the same as for Policy 1.

Evaluation Rule

This is the same as for Policy 1.

Preliminary Results

The preliminary results were interesting. This policy may produce results that are technically superior to the results obtained using Policy 1. Selected for large-sample investigation.

POLICY 6: INITIAL PRIOR MEANS, OPTIMISTIC

Summary of Policy Characteristics

Policy 6 is intended to show the effect of not using current information in the evaluation. It corresponds to an organizational situation in which the engineering group that is evaluating a given action, say a wind-tunnel test of wing design ω_A, has current information for the characteristics that will be measured by the given action, in this case $C_{D_{f}\omega_A}$ and e_{ω_A}. All other information items used in the evaluation

*Op. cit., p. 4.

are the means of the initial probability distributions for the "best" design at the beginning of the project. In other words, an engineering group receives current information about the characteristics that will be measured by an action taken by the group, but the only information that the group has regarding the other characteristics is the most likely estimate for the best design at the beginning of the project. This situation corresponds to an extreme deviation from the advice of Rule 4 of Klein, et al.* The calculation procedure is the same as for Policy 1 in all other respects. Policy 6 is labeled initial prior means, optimistic, to reflect the delayed information regarding the best design.

Eligibility Rule

This is the same as for Policy 1.

Forecasting Time and Cost

This is the same as for Policy 1.

Forecasting Performance

For the characteristics that are measured by the action being evaluated, the preposteriors are determined using Eqs. (9) and (10) as described under Policy 1 above. For all the other component characteristics, the means of the preposterior distributions are set equal to the means of the initial probability distributions for the design that yields the maximum expected performance incentive under the initial prior distributions. The standard deviations of the other component characteristics are set equal to zero. Then the propagation of uncertainty is used to determine the system performance preposteriors. This policy is called decentralized because when a given action is being evaluated, the only information available regarding the characteristics of the other components is the initial prior means. This is contrasted to Policy 1 where *all* of the *current* information is available; that is, there is a centralized source of all information.

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*Ibid., p. 5.

Evaluation Rule

This is the same as for Policy 1.

Preliminary Results

The sequences of actions are extremely long. This results in long time, high costs, and, consequently, low incentive pay-offs. However, the fact that so much search for a technically superior system was taking place was sufficient reason for running large samples with this policy.

POLICY 7: INITIAL PRIOR MEANS, PESSIMISTIC

Summary of Policy Characteristics

Policy 7 is a minor variation of Policy 6. It uses the means of the initial probability distributions for the "worst" design. Accordingly, Policy 7 is labeled "initial prior means, pessimistic."

Eligibility Rule

This is the same as for Policy 1.

Forecasting Time and Cost

This is the same as for Policy 1.

Forecasting Performance

The same as for Policy 6 except that the means of the preposterior distributions for the component characteristics not measured by the action being evaluated are set equal to the means of the initial probability distributions for the design that yielded the *minimum* expected performance incentive under the initial prior distributions. This policy is called pessimistic while Policy 6 is called optimistic because this policy uses the initial "worst" design for its technical information basis while Policy 6 uses the initial "best" design.

Evaluation Rule

This is the same as for Policy 1.

Preliminary Results

A sample run of three histories under this policy were identical to the first three sample runs under Policy 6.* Hence, this policy was not selected for large-sample investigation.

POLICY 8: PROBABILITY OF SUCCESS

Summary of Policy Characteristics

Policy 8 ignores the time and cost elements in making decisions and uses only the probability of technical success. Such a policy might be used when the contractor wants to maximize his chances of receiving production orders and he suspects that such orders will be decided on the basis of the system performance characteristics. Another situation that would be consistent with Policy 8 is when the contractor wants to maintain a reputation of technical success and does not care about time and cost. This policy is labeled probability of success. It could also be called minimize technical risk. This follows because one minus the probability of success equals the probability of failure.

Eligibility Rule

This is the same as for Policy 1.

Forecasting Time and Cost

The evaluation rule for this policy does not use time and cost information.

Forecasting Performance

This is the same as for Policy 1.

Evaluation Rule

Select the action that maximizes the probability of technical success. Technical success means that both system performance characteristics

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*The same initial random number was used in both cases.

are equal or superior to the zero performance incentive values, *PSRNMI* and *PSRGTO*. As defined here, the two performance characteristics are independent. Hence, the probability that both are successful is equal to the product of the probabilities that they are individually successful, or

$$
\begin{aligned}
&Pr(NMI/LB \geq PSRNMI,\ GTO\ WT \leq PSRGTO) \\
&\qquad = Pr(NMI\ LB \geq PSRNMI)Pr(GTO\ WT \leq PSRGTO), \qquad (29)
\end{aligned}
$$

where

$$
Pr(NMI\ LB \geq PSRNMI) = \tfrac{1}{2}ERFC\left[\frac{PSRNMI - E_{pp}(NMI\ LB)}{\sqrt{2}\ \sigma_{pp}(NMI/LB)}\right] \qquad (30)
$$

and

$$
Pr(GTO\ WT \leq PSRGTO) = 1 - \tfrac{1}{2}ERFC\left[\frac{PSRGTO - E_{pp}(GTO\ WT)}{\sqrt{2}\ \sigma_{pp}(GTO\ WT)}\right], \qquad (31)
$$

and all symbols are as defined above.*

Selecting the action that maximizes the probability of technical success is pursued until a deliver action becomes eligible. Then that deliver action is selected regardless of whether the result of the assemble and test yielded a technically successful system.

Preliminary Results

The outcomes are reasonable. Sequences of actions are frequently longer than the minimum required but not excessively long as with Policies 6 and 7. Policy 8 was selected for large-sample investigation.

POLICY 9: NO FAILURES DELIVERED

Summary of Policy Characteristics

Policy 9 is a minor variation of Policy 8. It attempts to eliminate the inconsistency in Policy 8 of selecting actions that maximize

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*Derivations of these expressions are presented in Appendix B.

the probability of technical success until a terminal action becomes eligible and then selecting that deliver action whether or not the system is a technical success. In Policy 9, the system that will be delivered is examined to make sure that it is a technical success before it is delivered. If it is not successful, then the development continues for the remaining designs until a successful system is achieved or all the designs are exhausted. Policy 9 is labeled no failures delivered.

Eligibility Rule

This is the same as for Policy 1.

Forecasting Time and Cost

This is the same as for Policy 8.

Forecasting Performance

This is the same as for Policy 1.

Evaluation Rule

The evaluation rule is the same as for Policy 8, except that when a delivery action is eligible, the system to be delivered is examined to see if it is technically successful. If it is, then it is delivered. If it is not, then the actions that have not yet been selected or preempted are picked using the maximize probability rule until another delivery is eligible. This is continued until a technically successful system is obtained or all (8) systems have been tried with none found successful. In the latter circumstance, the program writes out the message "Attempted all alternatives."

Preliminary Results

Several project histories failed to produce a technically successful system. Because this is not realistic,* the policy was not selected.

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*In the real world, repeated failure would lead to a redefinition of technical success. To make this policy realistic some rule for this redefinition would have to be incorporated. Comments on this are presented in Sec. VII.

V. RESULTS FROM THE SIMULATION

The decisionmaking policies and multiple incentive contracts considered in this study were first examined using preliminary samples of ten runs. Five policies and two contracts were selected for examination using larger samples. The sample size for these larger runs was determined by considering the statistical significance that could be achieved in relation to the computer time required.

Preliminary runs indicated that a good average figure for the time required per run was 1 minute. This meant that ten cases (five policies and two contracts) would require 10 hours with a sample size of 60. Allowing time for link-edit operations, 50 appeared to be a reasonable sample size.

The means and standard deviations of the final state attributes for some of the preliminary runs (sample size of 20, 18 degrees of freedom) were examined to determine what level of significance could be obtained with a two-tailed t-test comparison of the means for a sample size of 51 (100 degrees of freedom), assuming that the same results would be obtained. The findings are shown in Table 4. The first column shows the approximate t values, or range of t values, obtained from the preliminary runs. The second column shows the level of significance that the t values in column one would yield if the sample size had been 51 instead of 10.* The third column shows the level of significance that corresponds to a sample of 101. As the table shows, there is very little to be gained by increasing the sample size above 51; therefore, samples of 51 runs were obtained.

RESULTS

The outputs for each project history include the final state and history items listed in Sec. I. All output was obtained on punched

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*The percentage values in the table were obtained by linear interpolation between the values in a table of the percentage points of the t distribution. See Appendix Table 3 in Albert H. Bowker and Gerald J. Lieberman, *Engineering Statistics*, Prentice Hall, Englewood Cliffs, N.J., 1959.

Table 4

ANALYSIS OF PRELIMINARY t VALUES TO DETERMINE SAMPLE SIZE

Final State Attributes	$t_{calc,\ 18}$	$\alpha \mid t_{\alpha,100} = \left(\frac{51}{10}\right)^{\frac{1}{2}} t_{calc,\ 18}$	$\alpha \mid t_{\alpha,200} = \left(\frac{101}{10}\right)^{\frac{1}{2}} t_{calc,\ 18}$
Nautical miles per pound	1.5-2.0	<.0005-.0005	<.0005-...
Gross take-off weight	~.25	~.288	~.216
Payoff	1.43	.00087	<.0005
Cost	2.0-2.5	<.0005-...	<.0005-...
Time	2.0-2.5	<.0005-...	<.0005-...

cards to facilitate future analyses. For each action selected in any given history there are four cards that specify the means and standard deviations of the system performance characteristics. If N actions are selected in a given run, then there will be $4N$ cards for the means and standard deviations. There are two cards for each run that summarize the final state attributes and the sequence of actions. The final state attributes and the sequence of actions are also displayed in an easily readable format. This requires 5 cards if $N \leq 20$ and 7 cards if $N > 20$. Thus, there is a total of $4N + 7$ cards if $N \leq 20$ and $4N + 9$ cards if $N > 20$. A total of 459 (9×51) project histories were run. The distribution of the number of runs of various lengths, N, is shown below. This gives a total of 30,606 cards.

Run length	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
No. of runs	220	15	5	4	1	2	91	9	6	3	1	7	7	12	9	17	21	14	15

FINAL STATES OF THE DEVELOPMENT PROCESS

The means and standard deviations for the five attributes of the final state of the hypothetical system development project are shown in Table 5 for the five policies and two contracts that were subjected to large samples.

Table 5

MEANS AND STANDARD DEVIATIONS OF FINAL
STATE ATTRIBUTES BY POLICY

Final State Attributes	Policy 1 Maximize Expected Payoff		Policy 4 Current Means Analysis		Policy 5 Low Cost Actions First		Policy 6 Initial Prior Means, Optimistic		Policy 8 Probability of Success	
	Means	Stand Dev	Means	Stand Dev	Means	Stand Dev	Means	Stand Dev	Means	Stand Dev
Contract A--low incentive										
Nautical miles per pound	.095407±	.007754	.091121±	.010090	.096271±	.012613	.095340±	.014772	.095328±	.006899
Gross take-off weight, lb	128680±	2493	128496±	3485	128370±	2924	128314±	3386	129443±	2607
Payoff, $ × 10^{-3}	21080±	9560	20822±	10117	16495±	11556	-50723±	26931	9447±	23280
Cost, $ × 10^{-3}	304748±	465	304671±	0	305166±	0	321911±	4909	306903±	3811
Time, wks	128±	6	126±	0	144±	0	295±	40	149±	40
Contract B--high incentive										
Nautical miles per pound	.098215±	.006286	.095724±	.007547	.097283±	.008781	.099768±	.014089	.095328±	.006899
Gross take-off weight, lb	128671±	2901	128977±	3302	128035±	3306	128389±	2700	129443±	2607
Payoff, $ × 10^{-3}	38921±	69591	25704±	65942	41061±	74449	-38319±	66849	2230±	73979
Cost, $ × 10^{-3}	304801±	619	304671±	0	305941±	1716	326392±	2153	306903±	3811
Time, wks	128±	6	126±	0	151±	15	325±	19	149±	40

The system performance outcomes are presented in scatter diagram form in Fig. 12. The location of each outcome is identified by a number that corresponds to the system design (see Fig. 7) that was delivered. The axes of the diagrams are the same as in Fig. 8. As before, the diagonal lines locate the zero incentive payoffs for system performance. All points above these lines correspond to losses with respect to the system performance incentive, and points below the line correspond to gains.* The further the points are away from the line, the more negative, or positive, is the amount.

The four quadrants determined by the horizontal and vertical dashed lines are the same as in Fig. 8. Outcomes in Quadrant IV are successful with respect to both performance characteristics; outcomes in Quadrant II are unsuccessful with respect to both. In Quadrant I, outcomes are successful with respect to fuel economy but not with respect to gross take-off weight; in Quadrant III, the situation is reversed.

*The total payoff to the contractor also includes a fixed fee and the incentives with respect to time and cost.

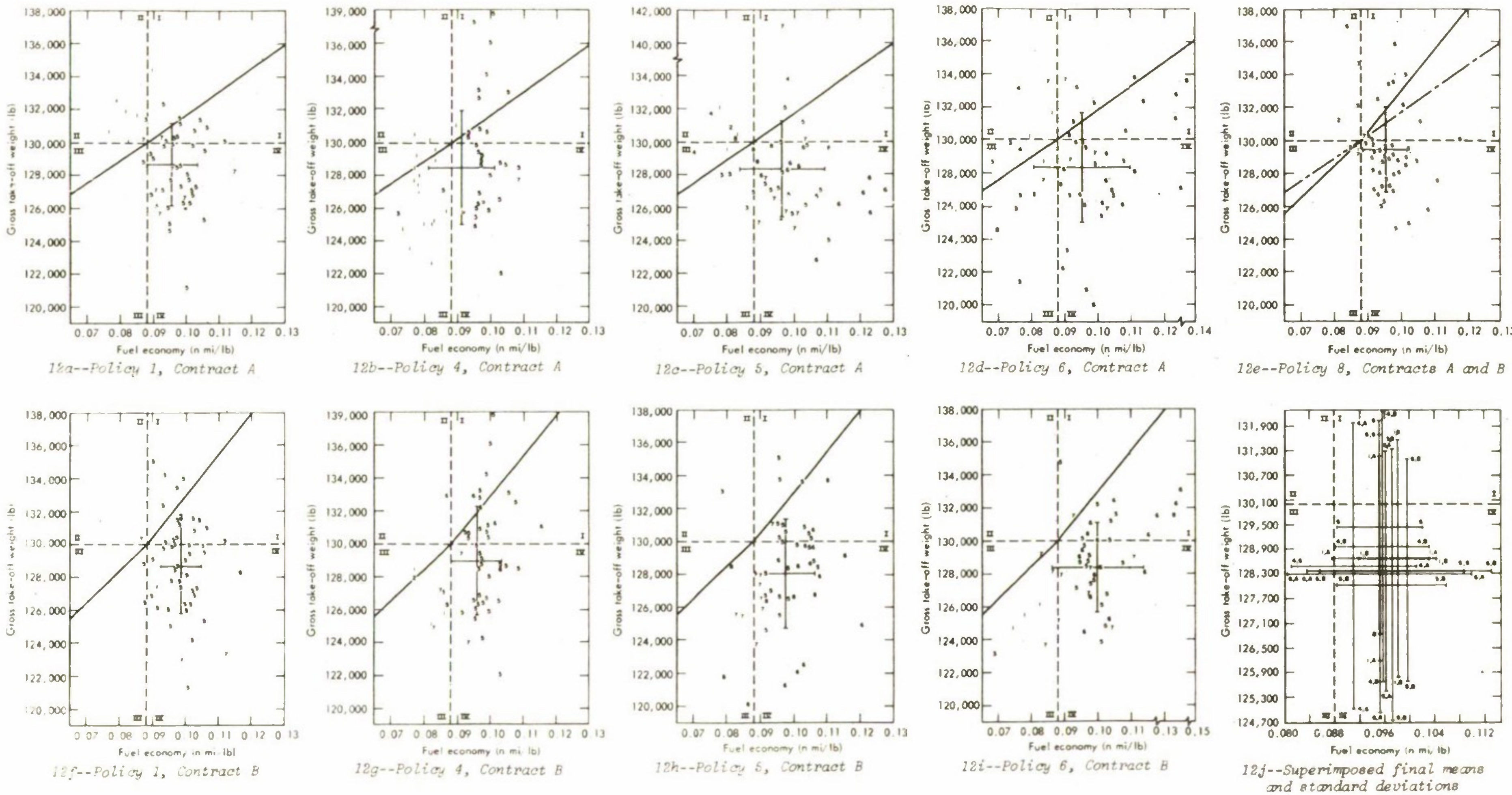

Fig. 12--Scatter diagrams for technical outcomes
(note different scale for 12j)

The crosses in the figures show the mean plus and minus the standard deviation of the technical outcomes for each contract and policy. All the crosses are combined in Fig. 12j.

Counting the system designs delivered in each diagram gives the frequencies of delivery shown in Table 6. Design S_5 is delivered far more frequently than any other design. Figure 8 shows why this is not surprising; design S_5 is initially the "best" design.

Counting the number of outcomes in each quadrant of the scatter diagrams yields the frequencies of technical success and failure for each contract and policy, as shown in Table 7.

Histograms for the five attributes are shown in Fig. 13. The data for these histograms were generated using the IBM Scientific Subroutine TAB1.* They were obtained only to display the shape of the distributions and not to make comparisons.

SEQUENCE OF ACTIONS

The sequences of actions generated under a given policy-contract combination have several characteristics. These characteristics can be analyzed in various ways depending on the available information.

Three interesting characteristics that can be examined using the data generated in this research are: Are the actions chosen in an order that is uncertainty reducing? What are the patterns in the order of selection? What are the reasons for sequences containing more than the minimum number of actions required by the eligibility rule?

The question of uncertainty reduction is one of the main issues in the author's previously referenced work.† Information regarding change in uncertainty over time that was generated during the present research will be analyzed at some future time.

In this study, only the patterns in the order of selection and the reasons for more than the minimum number of actions will be discussed. The obvious features of the sequences that will be examined include:

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* *System/360 Scientific Subroutine Package (360A-CM-03X) Version III Programmer's Manual*, 4th ed., H20-0205-3, International Business Machines Corporation, New York, 1968.

† Timson, op. cit., pp. 26-37.

Table 6

FREQUENCIES OF DELIVERY OF ALTERNATIVE SYSTEM DESIGNS

Policy	*Contract*	*System Design Delivered* S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
1	A	6	--	2	--	36	--	7	--
1	B	--	--	--	--	46	1	4	--
4	A	18	--	1	--	31	--	1	--
4	B	3	1	--	--	37	6	4	--
5	A	4	1	3	3	16	12	9	3
5	B	--	--	1	--	25	12	7	6
6	A	3	1	6	2	16	11	6	6
6	B	3	--	1	--	20	14	10	3
8	-	2	2	1	--	36	4	2	3

Table 7

FREQUENCIES OF TECHNICAL SUCCESSES AND FAILURES BY POLICY AND CONTRACT

Technical Outcomes (Quadrants I-IV)	*Policy 1*		*Policy 4*		*Policy 5*		*Policy 6*		*Policy 8*
	A	*B*	*A*	*B*	*A*	*B*	*A*	*B*	
Complete success (IV)	31	32	20	25	32	32	26	29	32
Partial success (I)	12	16	12	18	7	13	11	14	11
Partial success (III)	1	2	17	7	7	5	10	8	4
Complete failure (II)	7	1	2	1	5	1	4	--	4

A

B

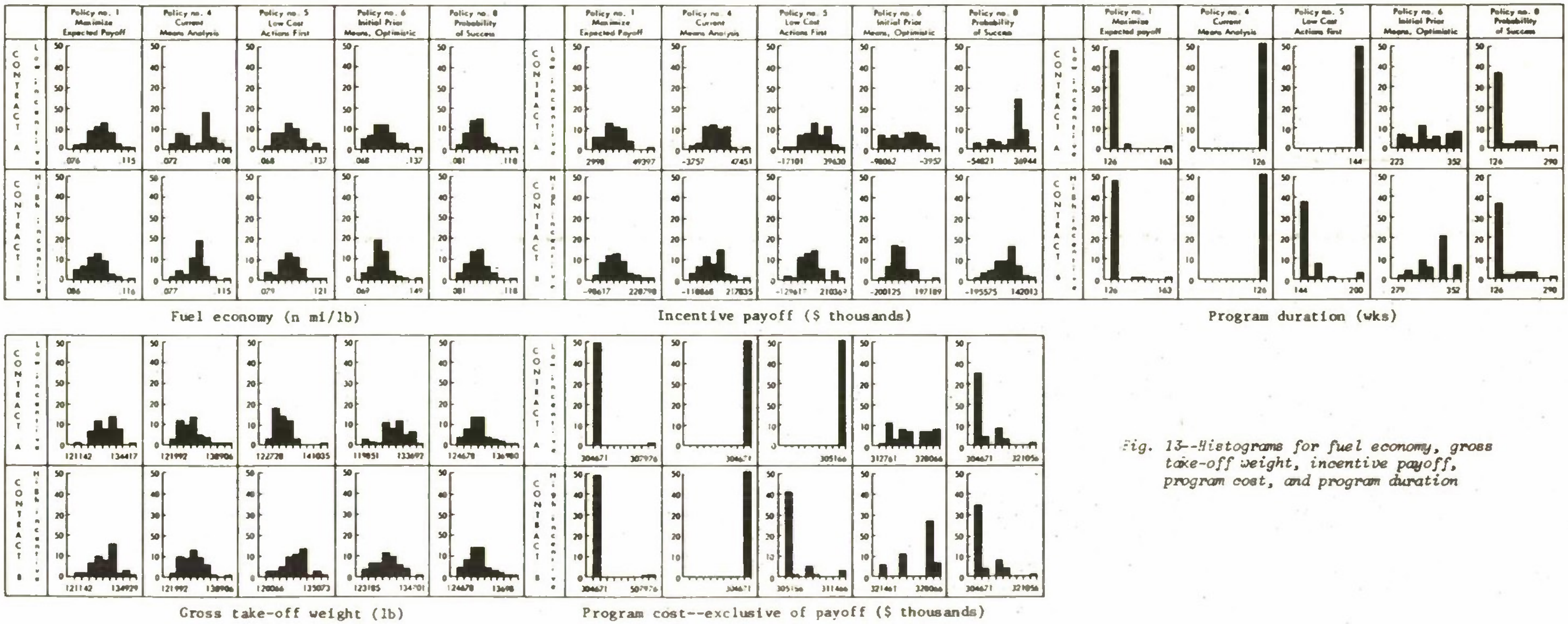

Fig. 13--Histograms for fuel economy, gross take-off weight, incentive payoff, program cost, and program duration

the most likely order of the first eight actions, a list of the actions always selected, a list of the actions never selected, the minimum number of actions required, the number of sequences having the minimum number of required actions, the average number of actions per history, and the average sequence number at which the last required experiment is executed. These items are shown in Table 8 for each policy and contract.

HISTORIES OF SYSTEM PERFORMANCE PROBABILITY DISTRIBUTIONS

The means and standard deviations of the system performance characteristics at each decision point can be used to trace the changes over time in the probability distributions and in measures such as the probability of technical success. These "histories" are closely related to the sequences in which the actions are selected and all will be analyzed in some future research.

Table 8

SUMMARY CHARACTERISTICS OF SEQUENCES OF ACTIONS

	Policy and Contract								
Item	*1, A*	*1, B*	*4, A*	*4, B*	*5, A*	*5, B*	*6, A*	*6, B*	*8*
Typical "early" sequence	41,29,43, 37,42,33, 21,25	41,29,43, 37,42,33, 21,25	43,42,41, 37,33,29, 25,21	43,42,41, 37,33,29, 25,21	25-32,41, 42,43,37, 23,33	25-32,41, 42,43,37, 21,33	29,37,24, 33,26,42, 31,27	29,37,24, 36,26,34, 27,42	25,33,41, 21,29,43, 37,42
Actions always selected	29,33,41, 42,43	29,41,42, 43	37,41,42, 43	37,41,42, 43	25-32,41, 42,43	25-32,41, 42,43	21,24,25, 26,27,28, 29,30,31, 33,34,36, 37,41,42, 43	21,23,24, 25,26,27, 28,29,30, 31,33,34, 36,37,41, 42,43	25,41,42, 43
Actions never selected	18,20,22, 24,26,28, 30,32,34, 35,36,38, 40	17,18,20, 24,28,32, 35,36,40	17,18,19, 20,24,26, 28,32,34, 36,38,39, 40	17,18,19, 20,24,28, 32,36,38, 39,40	19,35	35	35	35	32,35
Minimum number actions required	10	10	10	10	16	16	10	10	10
Number of minimum length sequences	42	44	51	51	51	39	0	0	32
Avg number actions/history	10.25	10.23	10	10	16	16.39	24.45	25.74	11.74
Avg number actions at which last experiment prerequisite satisfied	8.25	8.23	8	8	14	14.39	22.45	23.74	9.53
Avg number actions between end and prerequisites	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.21
Avg number actions beyond minimum	.25	.23	0	0	0	.39	14.45	15.74	1.74

VI. POLICY AND CONTRACT ANALYSIS AND COMPARISONS

The method for analyzing decisionmaking under aggregate uncertainty was structured to be used for the evaluation of alternative decisionmaking policies and multiple incentive contracts. To that end, this section demonstrates how the results can be analyzed.* However, it is imperative that the reader keep in mind that conclusions drawn from these analyses are valid only for the hypothetical project studied here. Before making any broad generalizations, it is necessary to examine many projects to discover the conditions that favor alternative policies and contracts.

In this section, the results described in Sec. V are analyzed from three points of view. First, comparisons are made between the results obtained under the two contracts used in the large sample runs. Second, comparisons are made between the results obtained for the five decisionmaking policies used in the large sample runs. Third, the results are compared to some of the earlier studies.

COMPARISONS BETWEEN CONTRACTS

Comparisons between the results obtained under Contract A and Contract B are made for each decisionmaking policy. Hence, the results of Contract A and Policy 1 are compared to the results of Contract B and Policy 1. Comparing the results of Contract A and Policy 1 to the results of Contract B and any other policy would be meaningless.

The comparisons are made in terms of the final state attributes, the frequencies of the choices, and the sequences of actions.

Final State Attributes

The procedure for making comparisons using the final state attributes is to first test for a significant difference between the variances

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*This section is highly analytical, and readers who are not interested in extensive *F*- and *t*- ratio analyses can skip to Sec. VII without impairing their understanding of the methodology described in this study. The findings of this section are summarized in Table 12 in the next section.

of a given attribute. This is done using a two-tailed F test at the 5 percent level of significance.* The number of degrees of freedom for all cases is 100. Hence, at the 5 percent level, the variances are considered to be equal if

$$1.75 \geq F \geq .571, \qquad (32)$$

where F is the calculated value of the F statistic.

If the variances are not significantly different, then a t test at the 5 percent level of significance is used to test for a significant difference between the means. In these cases the number of degrees of freedom is 100, and the means are considered to be equal if

$$|t| \geq t_{.025,100} = 1.984, \qquad (33)$$

where $|t|$ is the magnitude of the calculated value of the t statistic, and $t_{.025,100}$ is the table value of t at the 2.5 percent level for 100 degrees of freedom.

If the variances are significantly different, then a t' test at the 5 percent level of significance is used to test for a significant difference between the means. In these cases the number of degrees of freedom must be calculated and a different value of the t' statistic must be obtained from a table of the t distribution. As above, the means are considered to be equal if the magnitude of the calculated t' is greater than or equal to the table value.

The results of the comparisons are shown in Table 9. Note that the means of the payoffs are not compared. This is because the mean payoff under any contract can be adjusted to any desired level by changing the fixed fee component of the contract.

The comparisons lead to the following general conclusions:

- *Technical Performance.* Using a higher rate of incentive on performance characteristics (Contract B) appears to be superior

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*Discussion of these tests can be found in most standard statistics texts such as Bowker, op. cit.

Table 9

CONTRACT A (LOW INCENTIVE) COMPARED TO CONTRACT B (HIGH INCENTIVE) USING FINAL STATE ATTRIBUTES FOR RUNS MADE WITH POLICIES 1, 4, 5, AND 6

Final State Attributes	Results: Contract A Mean	Results: Contract A Standard Deviation	Results: Contract B Mean	Results: Contract B Standard Deviation	F Calc	Variances Different at 5% Level?	t Calc	Degrees of Freedom	$t_{2.5\%}$	Means Different at 5% Level?	Paired Observations: t Calc	Paired Observations: Means Different at 5% Level?
Policy 1												
NMI/LB[a]	.095407	.007754	.098215	.006286	1.522	No	-2.009	100	1.984	Yes	2.465	Yes
GTO WT[b]	128680	2493	128671	2901	.738	No	.017	100	1.984	No	.027	No
Payoff[c]	21080	9560	38921	69591	.019	Yes	---	---	---	---	---	---
Cost[c]	304748	465	304801	619	.564	Yes	-.489	95	1.986	No	.191	No
Time, wks	128	6	128	6	1.000	No	.000	100	1.984	No	.496	No
Policy 4												
NMI/LB[a]	.091121	.010090	.095724	.007547	1.787	Yes	-2.609	94	1.986	Yes	4.021	Yes
GTO WT[b]	128496	3485	128977	3302	1.114	No	-.715	100	1.984	No	2.074	Yes
Payoff[c]	20822	10117	25704	65942	.024	Yes	---	---	---	---	---	---
Cost[c]	304671	0	304671	0	1.000	No	.000	100	1.984	No	.000	No
Time, wks	126	0	126	0	1.000	No	.000	100	1.984	No	.000	No
Policy 5												
NMI/LB[a]	.096271	.012613	.097283	.008781	2.063	Yes	-.470	91	1.987	No	---	---
GTO WT[b]	128370	2924	128035	3306	.782	No	.542	100	1.984	No	---	---
Payoff[c]	16495	11556	41061	74449	.099	Yes	---	---	---	---	---	---
Cost[c]	305166	0	305941	1716	.000	Yes	-3.225	50	2.009	Yes	---	---
Time, wks	144	0	151	15	.000	Yes	-3.333	50	2.009	Yes	---	---
Policy 6												
NMI/LB[a]	.095340	.014772	.099768	.014089	1.099	No	-1.549	100	1.984	No	---	---
GTO WT[b]	128314	3386	128389	2700	1.573	No	-.124	100	1.984	No	---	---
Payoff[c]	-50723	26931	-38319	66849	.024	Yes	---	---	---	---	---	---
Cost[c]	321911	4909	326392	2153	5.199	Yes	-5.970	69	1.996	Yes	---	---
Time, wks	295	40	325	19	4.432	Yes	-4.838	72	1.994	Yes	---	---

[a] NMI/LB = nautical miles per pound.

[b] GTO WT = gross take-off weight, in pounds.

[c] $ × 10^{-3}.

in terms of the performance values obtained than using a low incentive rate (Contract A). Table 9 shows that the mean fuel economy obtained under Contract B is superior to that obtained under Contract A for all policies. This result is significant at the 5 percent level for two of the policies. The results for the gross take-off weight are mixed and no conclusion can be drawn.

- *Payoff*. The higher rate of incentive on performance (Contract B) produces overwhelmingly more variance on payoff than does a lower rate (Contract A).*
- *Time and Cost*. The higher rate of incentive on technical performance (Contract B) stimulates more search than a lower rate (Contract A). The fact that times and costs are higher means more actions were taken; hence, there was more search. This result is very significant for Policies 5 and 6. The comparisons for Policies 1 and 4 do not support this distinction; however, there are good reasons for ignoring these inconsistencies, which are discussed below.

Looking at the final states obtained using Policy 1, it is observed that 33 of the final states obtained under Contract A are identically obtained under Contract B. In addition, 3 more final states have the same airframe, and another has the same airplane efficiency factor. This leaves only 14 cases in which the final state attributes are totally different. Consequently, the effective sample size for comparisons between contracts is severely reduced.

The reason for these identical runs is that all large-sample runs were started with the same random number. The random number generator used is a "pseudo random number generator" and, consequently, if it is called the same number of times on two separate runs that begin

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*The evaluation rule for Policy 8 is independent of the contract; hence, all final state attributes except payoff will be the same under any contract. Comparing the payoff variances for Policy 8 gives an *F* value of .162 which shows a significant difference.

with the same random number, then the final random number will be the same for both cases.

Policy 4 also has several identical and similar runs for the two contracts.* However, there is a mechanical reason that explains this high degree of similarity. The evaluation rule for Policy 4 does not consider the dispersion of possible results. It uses a single "best" estimate of the outcome. Consequently, all project runs using Policy 4 are completed in the minimum number of required actions. Furthermore, the actions are always picked in descending numerical order. This is also a result of basing all evaluations on a single-valued estimate of the technical results. These two phenomena result in the pseudo random number generator being called the same number of times for every run, and the actions selected at each decision point are almost always the same.

Regardless of the reason why so many runs in a sample are identical, the fact that they occur is an interesting result. It means that if the contractor uses either Policy 1 or Policy 4, then the chances are quite high that identical outcomes will be obtained regardless of a factor of ten change in the rate of performance incentives. However, in spite of this high degree of identical behavior, the fuel economy obtained under the high incentive contract (Contract B) is significantly superior to that obtained under the low incentive contract (Contract A).

When a large number of runs turn out to be identical, the power of the statistical analysis can be improved by using the test for equality of the means of two samples when the observations are paired.† The results of this test are shown in the two extreme right columns in Table 9. The degrees of freedom are 50 and the table value of $t_{.025}$ is 2.009. The only major change between the results without paired observations and the new results is that for Policy 4 the difference between the gross take-off weights is significant at the 5 percent level using the paired observations test and it is not significant using the t test without paired observations.

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*There are 32 identical runs, 9 that have the same airframe, and 2 that have the same airplane efficiency factor.

†This test is described in Bowker, op. cit., pp. 175-179.

The choice between using the same initial random number for all sample runs or a different number depends on what is important. If it is more important that the similarities or differences between the samples be indicated by the same statistical test, then different initial random numbers should be used. If it is more important to discover a high degree of identical behavior, then the same initial random numbers should be used.

Frequencies of Choices

In terms of the frequencies of technical success and failure, the high incentive contract (Contract B) results in more technical successes and more outcomes that are satisfactory with regard to fuel economy and are overweight than the low incentive contract (Contract A).* In terms of the frequencies of system design choices, the high incentive contract (Contract B) results in more choices of system designs S_5 and S_6 than does the low incentive contract (Contract A). Also, the low incentive contract (Contract A) results in more choices of system designs S_1, S_3, and S_4.†

The frequencies of design choices are not surprising considering the engine used in the various designs and Fig. 8. The lines of constant payoff for the two contracts are slightly rotated with respect to each other with the effect that the low incentive contract (Contract A) places more relative incentive on gross take-off weight than does the high incentive contract (Contract B). System designs S_1, S_3, and S_4 use the lower weight and lower fuel economy engine (E_A), while designs S_5 and S_6 use the higher weight and higher fuel economy engine (E_B). On Fig. 8, the initial probability distributions for designs S_5 and S_6 are farther into the positive payoff region of the high incentive contract (Contract B) than for the low incentive contract (Contract A). Also, design S_1 is farther into the positive payoff region of Contract A than of Contract B and designs S_3 and S_4 are not as far into the negative payoff region of Contract A than of Contract B.

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*See Table 7.

†See Table 6.

Sequence of Actions

The only comparisons that can be made using the sequences of actions are concerned with the amount of search. The general impression given by the items in Table 8 is that the high incentive contract (Contract B) generates more search than the low incentive contract (Contract A). More search would be expected to occur when a larger number of actions are always selected. This is true for Policy 6 that shows 17 actions always selected under Contract B and 16 actions always selected under Contract A.

Similarly, less search would be expected when more actions are never selected. This is indicated by Policy 1 (13 actions under Contract A and 9 under Contract B were never selected), Policy 4 (13 actions under Contract A and 11 under Contract B were never selected), and Policy 5 (2 actions under Contract A and 1 under Contract B were never selected).

More obvious indications of longer search are the average number of actions per simulated project, the average number (serial) action at which the last prerequisite experiment is satisfied and the average number of actions beyond the minimum required by the eligibility rule. All three of these indications show that the high incentive contract (Contract B) generates longer search than the low incentive contract (Contract A) for Policies 5 and 6. Since these three measures are closely related, this evidence should not be inferred to be three times as strong as for any one of the indicators.

COMPARISONS BETWEEN POLICIES

The five decisionmaking policies used in the large-sample runs were formulated with specific comparisons in mind. The eligibility rule, forecasting techniques, and evaluation rule used in Policy 1 are representative of the kind of characteristics that are desirable in a decisionmaking policy. Thus, Policy 1 constitutes a proximate criterion against which all other policies are compared.

The four comparisons are: (1) Policy 1 (complete preposterior analysis of the performance probability distributions) compared to Policy 4 (performance represented by current prior means); (2) Policy 1 (one action from each category) compared to Policy 5 (all weight estimates and small aircraft wind tunnel tests first, then one each); (3) Policy 1 (complete preposterior analysis of the performance probability distributions) compared to Policy 6 (preposterior analysis of characteristics measured but initial prior means for all others); and (4) Policy 1 (maximize expected payoff) compared to Policy 8 (maximize probability of technical success). As with the contract comparisons, it is meaningless to compare the results of one contract and policy, say, Contract A and Policy 1, to the results of the other contract and any other policy, say, Contract B and Policy 4.

The comparisons are made in terms of the final state attributes, the frequencies of choices, and the sequences of actions.

Final State Attributes

The statistical procedures are the same as described above. The results are shown in Table 10.

Policy 4 Compared to Policy 1. Comparing Policy 4 (current prior means) to Policy 1 (preposteriors), the following conclusions may be drawn:

1. *Technical Performance.* Using the complete preposterior analysis (Policy 1) yields superior fuel economy as compared to using only the prior means. This result is significant at the 5 percent level for Contract A. The gross take-off weight results are mixed.
2. *Payoff.* The comparisons show no significant difference.
3. *Time and Cost.* Policy 1 exhibits consistently more variable and higher times and costs. All of these results are significant at the 5 percent level except the mean costs.

Policy 5 Compared to Policy 1. Comparing Policy 5 (all low cost actions first) to Policy 1 (one action from each category), the following conclusions may be drawn:

1. *Technical Performance.* The fuel economy results are mixed and not significant. The gross take-off weight results are consistent but still not significant.

Table 10

COMPARISON OF POLICY 1 (COMPLETE PREPOSTERIOR ANALYSIS) WITH POLICIES 4 (CURRENT MEANS ANALYSIS), 5 (ALL LOW-COST ACTIONS FIRST), 6 (INITIAL PRIOR MEANS ANALYSIS), AND 8 (PROBABILITY OF SUCCESS) FOR CONTRACT A AND CONTRACT 8

Contract A--Low Incentive

Final State Attributes	Results: Policy 1 Mean	Results: Policy 1 Standard Deviation	Results: Policy X Mean	Results: Policy X Standard Deviation	F calc	Variances Different at 5% Level?	t calc	Freedom	$t_{2.5\%}$	Means Different at 5% Level
	Policy 1		Policy 4							
NMI/LB[a]	.095407	.007754	.091121	.010090	.591	No	2.405	100	1.984	Yes
GTO WT[b]	128680	2493	128496	3485	.512	Yes	.307	92	1.986	No
Payoff[c]	21080	9560	20822	10117	.893	No	.132	100	1.984	No
Cost[c]	304748	465	304671	0	.000	Yes	-1.183	50	2.009	No
Time, wks	128	6	126	0	.000	Yes	-2.380	50	2.009	Yes
	Policy 1		Policy 5							
NMI/LB[a]	.095407	.007754	.096271	.012613	.378	Yes	-.417	84	1.989	No
GTO WT[b]	128680	2493	128370	2924	.727	No	.576	100	1.984	No
Payoff[c]	21080	9560	16495	11556	.684	No	2.183	100	1.984	Yes
Cost[c]	304748	465	305166	0	.000	Yes	6.420	50	2.009	Yes
Time, wks	128	6	144	0	.000	Yes	19.044	50	2.009	Yes
	Policy 1		Policy 6							
NMI/LB[a]	.095407	.007754	.095340	.014772	.276	Yes	.029	77	1.992	No
GTO WT[b]	128680	2493	128314	3386	.542	Yes	.622	94	1.986	No
Payoff[c]	21080	9560	-50723	26931	.126	Yes	17.943	63	1.996	Yes
Cost[c]	304748	465	321911	4909	.009	Yes	-24.857	51	2.009	Yes
Time, wks	128	6	295	40	.023	Yes	-29.486	52	2.008	Yes
	Policy 1		Policy 8							
NMI/LB[a]	.095407	.007754	.095328	.006899	1.263	No	.054	100	1.984	No
GTO WT[b]	128680	2493	129443	2607	.914	No	-1.511	100	1.984	No
Payoff[c]	21080	9560	9447	23280	.169	Yes	3.301	67	1.997	Yes
Cost[c]	304748	465	306903	3811	.015	Yes	-4.009	52	2.008	Yes
Time, wks	128	6	149	40	.023	Yes	-3.708	52	2.008	Yes

Contract B--High Incentive

Final State Attributes	Results: Policy 1 Mean	Results: Policy 1 Standard Deviation	Results: Policy X Mean	Results: Policy X Standard Deviation	F calc	Variances Different at 5% Level	t calc	Degrees of Freedom	$t_{2.5\%}$	Means Different at 5% Level
	Policy 1		Policy 4							
NMI/LB[a]	.098215	.006286	.095724	.007457	.694	No	1.811	100	1.984	No
GTO WT[b]	128671	2901	128977	3302	.772	No	-.497	100	1.984	No
Payoff[c]	38921	69591	25704	65942	1.114	No	.985	100	1.984	No
Cost[c]	304801	619	304671	0	.000	Yes	-1.450	50	2.009	No
Time, wks	128	6	126	0	.000	Yes	-2.380	50	2.009	Yes
	Policy 1		Policy 5							
NMI/LB[a]	.098215	.006286	.097283	.008781	.512	Yes	.616	92	1.986	No
GTO WT[b]	128671	2901	128035	3306	.770	No	1.033	100	1.984	No
Payoff[c]	38921	69591	41061	74449	.874	No	-.150	100	1.984	No
Cost[c]	304801	619	305941	1716	.130	Yes	-4.463	63	1.999	Yes
Time, wks	128	6	151	15	.160	Yes	-10.167	66	1.997	Yes
	Policy 1		Policy 6							
NMI/LB[a]	.098215	.006286	.099768	.014089	.199	Yes	-.719	70	1.995	No
GTO WT[b]	128671	2901	128389	2700	1.154	No	.508	100	1.984	No
Payoff[c]	38921	69591	-38319	66849	1.084	No	5.716	100	1.984	Yes
Cost[c]	304801	619	326392	2153	.083	Yes	-68.828	59	2.001	Yes
Time, wks	128	6	325	19	.010	Yes	-70.608	60	2.000	Yes
	Policy 1		Policy 8							
NMI/LB[a]	.098215	.006286	.095328	.006899	1.263	No	.054	100	1.984	No
GTO WT[b]	128671	2901	129443	2607	.914	No	-1.511	100	1.984	No
Payoff[c]	38921	69591	2230	73979	.885	No	2.580	100	1.984	Yes
Cost[c]	304801	619	306903	3811	.015	Yes	-4.009	52	2.008	Yes
Time, wks	128	6	149	40	.023	Yes	-3.708	52	2.008	Yes

[a] NMI/LB = nautical miles per pound.

[b] GTO WT = gross take-off weight, in pounds.

[c] $ \$ \cdot 10^{-3}$.

2. *Payoff.* The results are mixed. The one significant comparison (for Contract A) shows that requiring all low cost actions to be done first (Policy 5) reduces the payoff. This is expected because the time and cost incentives are the same for both policies.
3. *Time and Cost.* Requiring the low cost actions to be done first (Policy 5) very significantly increases the mean time and the mean cost. The comparisons of the variances are not clear. For the low incentive contract (Contract A) the time and cost variances are significantly less for Policy 5. The opposite is true for the high incentive contract (Contract B).

Policy 6 Compared to Policy 1. Comparing Policy 6 (initial prior means) to Policy 1 (preposteriors), the following conclusions may be drawn:

1. *Technical Performance.* Using the initial prior means for the initial best design for those characteristics not measured (Policy 6) instead of the complete distributions (Policy 1) results in a higher variance in the fuel economies for both contracts. The gross take-off weight shows a significantly higher variance for the low incentive contract. The means show no significant difference.
2. *Payoff.* The complete preposterior analysis (Policy 1) is far superior to the initial prior means analysis (Policy 6) for both contracts. The variance under Policy 6 is also significantly greater than under Policy 1.
3. *Time and Cost.* The initial prior means analysis (Policy 6) produces very significantly higher means and variances of both time and cost for both contracts.

Policy 8 Compared to Policy 1. Comparing Policy 8 (probability of success) to Policy 1 (expected payoff), the following conclusions may be drawn:

1. *Technical Performance.* The results are independent of the contract. Neither performance characteristic comparison is significant at the 5 percent level.

2. *Payoff.* The payoff using the expected payoff rule (Policy 1) is significantly superior to the payoff using the probability of success rule (Policy 8) for both contracts.
3. *Time and Cost.* The results are independent of the contract. The means and variances of both the time and the cost are significantly higher using Policy 8 than using Policy 1.

Frequencies of Choices

Comparisons between Policy 1 and Policies 4, 5, 6, and 8 in terms of the frequencies of technical successes and design choices are summarized in Table 11. The general conclusion that these comparisons lead to is that Policy 1 is as good or better than the other policies in terms of technical successes--e.g., outcomes in Quadrant IV (see Table 7). Also, Policy 1 is more likely to result in outcomes that are complete technical failures--e.g., outcomes in Quadrant II. However, the absolute number of technical successes is several times the number of

Table 11

COMPARISONS BETWEEN POLICY 1 AND POLICIES 4, 5, 6, AND 8 IN TERMS OF FREQUENCIES OF TECHNICAL SUCCESSES AND DESIGN CHOICES

Item	*More Outcomes for Policy 1*	*Approximately Same No. of Outcomes for Both Policies*	*More Outcomes for Policy N*	*Unclear as to Dominance*
Policy 4				
Quadrant	II, IV		I, III	
System design	S_3, S_5, S_7	S_4, S_8	S_1, S_2, S_6	--
Policy 5				
Quadrant	I, II	IV	III	
System design	S_1, S_5		S_2, S_3, S_4, S_6, S_7, S_8	--
Policy 6				
Quadrant	I, II, IV		III	
System design	S_5	--	S_2, S_3, S_4 S_6, S_8	S_1, S_7
Policy 8				
Quadrant	I, II	IV	III	
System design	S_1, S_3, S_7	S_4, S_5	S_2, S_6, S_8	--

NOTE: The assignment of the results into one of the four quadrants is according to their relation to two zero-incentive performance values--.088 n mi/lb and 130,000 lb. The specific quadrants are defined as follows: The aircraft is I: inferior in weight, superior in fuel economy; II: inferior in regard to both zero-incentive values; III: inferior in fuel economy, superior in weight; and IV: superior in regard to both zero-incentive values.

complete failures.* The other policies are more likely to result in outcomes that are superior with regard to weight but inferior with regard to fuel economy--e.g., outcomes in Quadrant III.

With regard to the system design that is ultimately delivered, Policy 1 is more likely to select S_5, while the other policies are more likely to select S_2 and S_6. There appears to be a tendency for Policy 1 to select the odd-numbered designs while the other policies tend to select the even-numbered designs. The odd-numbered designs have the low aspect ratio wing and the even-numbered designs have the high aspect ratio wing.†

Sequences of Actions

As with the comparisons between contracts above, the sequences of actions are useful only to analyze the amount of search. The general impression given by the information in Table 8 is consistent with the statistical tests regarding the times and costs as reported above. Policy 1 (complete preposterior analysis) generates longer searches than Policy 4 (current prior means analysis), but the difference is not large. The average number of actions for Policy 1 is 10.25 under Contract A (low incentives) and 10.23 under Contract B (high incentives) and for Policy 4 it is 10 for both contracts. The average number of actions for Policy 5 (all low cost actions first) and for Policy 6 (initial prior means analysis) are overwhelmingly greater than for Policy 1. The Policy 8 (probability of success rule) histories are moderately longer.

An interesting difference exhibited by Policy 8 is that it is the only policy that evidences search after the minimum requirements of the eligibility rule are satisfied. The second to the last row in Table 8 shows the average number of actions between the end of the project and the action that satisfied the last experiment prerequisite.‡ For all

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*See Table 7.

†See Fig. 7.

‡Recall that an assemble and test action cannot be selected until a minimum of one action has been selected from each experiment activity category.

policies and contracts, except Policy 8, this number is 2.00. For Policy 8, it is 2.21. Two actions are required to terminate a simulated project after the last prerequisite experiment is completed--specifically, one assemble and test, and one deliver. Hence, all policies except Policy 8 exhibit no search after the last experiment prerequisite is satisfied. The 2.21 figure for Policy 8 can be interpreted that 21 percent of the time, on the average, one additional action is selected after the last experiment prerequisite is satisfied.

COMPARISONS WITH EARLIER STUDIES

In the present research, the final state of the system development project is characterized by the five attributes: fuel economy, gross take-off weight, payoff, program cost, and time. The "goodness" of a decisionmaking policy can be judged in terms of these attributes. It is important to note that there are two points of view for judging--the customer's and the contractor's.

Economic Studies and the Contractor's Point of View

Most of the earlier studies that have used economic analysis of decisionmaking have asserted that from the contractor's point of view optimal policies are those that maximize expected payoff.* Consulting Table 5 shows that Policy 1 yields the highest expected payoff with one exception: Policy 5 (all low cost actions first) and Contract B (high incentives). Table 10 shows that the comparison is significant for Policies 6 and 8 but not for Policies 4 and 5. Hence, the exception can be ignored, and Policy 1 is adjudged superior where the differences are significant. From this it is inferred that the characteristics of Policy 1 are superior to the characteristics of Policies 6 and 8. This is evidence of the superiority of using current technical information in decisionmaking as opposed to old information (Policy 1 vs. Policy 6) and of the superiority of using an evaluation rule that is based on the

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*T. A. Marschak and J. A. Yahav, "The Sequential Selection of Approaches to a Task," *Management Sciences*, Vol. 12, No. 9, May 1966, pp. 627-647.

expected payoff as opposed to one that is based on only the technical outcome (Policy 1 vs. Policy 8).*

The Five Rules and the Customer's Point of View

The five rules of Klein, et al.,† are more concerned with the customer's point of view than with the contractor's. The first rule relates to the amount of detail in the system specification and is beyond the scope of the present study.

The second rule, which says that preliminary analysis should be made on a number of alternatives, is represented by Policy 5 (all low-cost actions first). The rule implies that Policy 5 should be superior to Policy 1 (one action from each category). However, Table 10 shows that there is a consistent (i.e., for both contracts) lack of difference between the two policies for the performance characteristics of the system. Furthermore, Policy 5 is consistently different for time and cost, both of which are higher because of the additional actions required by Policy 5. However, under Contract A (low incentives), the payoffs are significantly different and Table 5 shows that Policy 5 is superior in this regard.‡

Rule 3 deals with the timing of major financial commitment to a system configuration. None of the policies used in this study are related to this rule.

Policy 6 (initial prior means analysis) is concerned with Rule 4, which suggests that new information should be rapidly transmitted to technical decisionmakers. It represents extreme departure from the advice of Rule 4, while Policy 1 (complete preposterior analysis) represents strict adherence. Again, there is a consistent lack of difference between the two policies for the system performance characteristics and there is a consistent difference for the costs and times. In this case, the difference is in accordance with the rule. Also, the

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*Even more interesting is the fact that for the project used in this study, the rule to maximize the probability of technical success did not produce a technically superior product.

†Op. cit., pp. 4-5.

‡From the customer's point of view, a lower payoff is superior because a payoff is money out of his pocket.

payoffs are consistently different, but, from the customer's point of view, in a direction that makes Policy 1 inferior.

Rule 5 is concerned with early testing of components. There are no early test actions in the system development project used in this study; hence, this rule is not examined.

VII. CONCLUSIONS, REFINEMENTS, AND EXTENSIONS

CONCLUSIONS

This research was undertaken to demonstrate an approach to the analysis of decisionmaking in system development that combines evaluation at the system and program level with actions taken at lower levels in the work breakdown structure. This "linking-up," or unification, is made possible by the use of system performance design equations in a manner previously described by the author.* The demonstration involved the development and use of a computer simulation model of a system development project.

The present effort highlights two important areas of application. First, the computer simulation approach appears to be an extremely useful method for analyzing decisionmaking policies and contracts under a variety of conditions. The present model demonstrates the capability, but some extensions and modifications are required to make the simulated project more realistic. These additions include such items as more detailed system test actions. Several points will be elaborated below.

The second area of application is risk assessment. The hierarchy of uncertainty presents probabilistic information regarding the techcal outcomes for each system design. This information can be used for technical risk assessment. Policy 8 (probability of success) is a risk criterion. The probability of technical success is equal to one minus the probability of technical failure, by definition. Furthermore, parametric cost-estimating techniques make it possible to extend the procedure to cost-risk assessment. This is commented on briefly below.

The general picture is that Policy 1 (maximize expected payoff) is superior to all other policies. In terms of the differences between the elements of the policies this implies that

- o Complete preposterior analysis is superior to analysis based only on the current prior means (Policy 4), and it is also superior to analysis based on the initial prior means for the characteristics not measured (Policy 6).

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*Timson, op. cit., pp. 5-18.

- Requiring that all low cost actions be done first (Policy 5) is inferior to not so requiring.
- Evaluation based on the expected payoff--i.e., incorporating time and cost considerations--is superior to evaluation based on the probability of technical success (Policy 8) alone.

It is important to note that the evidence for the superiority of Policy 1 is largely concentrated in those items that relate to the amount of search--i.e., time, cost, and sequence of actions. If the contractor can persuade the customer to change the time and cost incentive depending on the decision policy, then there could be changes in the results. This would be especially true of Policy 5. Under this policy, the minimum number of actions taken is greater than for all other policies. If this is desired by the customer, then he should increase the compensation to the contractor for the extra effort.

It is important to repeat the caveat that the conclusions are valid only for the conditions of the hypothetical project used in this study. Other projects with other conditions might yield different conclusions. An overall view of the conclusions that may be drawn from the comparisons between the policies are summarized in Table 12. For each possible comparison, the table shows the number of the superior policy. If the comparisons showed mixed results for the two contracts, then "unclear" is entered. If the results are not significant at the 5 percent level or better, then "insignificant" is entered.

The general conclusions that may be drawn from the comparisons between Contract A (low incentive) and Contract B (high incentive) are summarized as follows:

- *Nautical Miles per Pound (NMI/LB).* Contract B is better than Contract A, but two out of four comparisons are insignificant.
- *Gross Take-off Weight (GTO WT).* The results are unclear. Three out of four comparisons are insignificant.
- *Payoff.* Contract B has a higher variance.
- *Cost.* Contract A is better than Contract B, but two out of four comparisons are insignificant.
- *Time.* Contract A is better than Contract B, but two out of four comparisons are insignificant.

Table 12

SUMMARY OF COMPARISONS BETWEEN POLICIES

Policies Compared	Final State Attributes					Frequency of Successes	Sequences of Actions
	Nautical Miles per Pound	*Gross Take-off Weight*	*Payoff*	*Cost*	*Time*		
Complete preposterior analysis (Policy 1) compared with current prior means analysis (Policy 4)	Policy 1	Unclear Insignificant	Policy 1 Insignificant	Policy 4 Insignificant	Policy 4	Policy 1	Policy 4
One action from each category (Policy 1) compared with all low-cost actions first (Policy 5)	Unclear Insignificant	Policy 5 Insignificant	Unclear	Policy 1	Policy 1	Unclear	Policy 1
Complete preposterior analysis (Policy 1) compared with initial prior means analysis (Policy 6)	Unclear Insignificant	Policy 6 Insignificant	Policy 1	Policy 1	Policy 1	Policy 1	Policy 1
Expected payoff rule (Policy 1) compared with probability of success rule (Policy 8)	Policy 1 Insignificant	Policy 1 Insignificant	Policy 1	Policy 1	Policy 1	Unclear	Policy 1

NOTE: Unclear means that the comparisons showed mixed results. Insignificant signifies that the results were not significant at the 5 percent level or better.

- *Frequency of Success.* Contract B is better than Contract A.
- *Sequences of Actions.* Contract A is better than Contract B.

The general picture given by the conclusions is that high incentives on the system performance characteristics stimulate more search for a technically superior product.* This search results in improved fuel economy performance and more technical successes for all policies that are sensitive to incentives. The improvement is significant at the 5 percent level for two of the four policies. However, the increased search means higher costs and longer times and higher uncertainty regarding the incentive payoff. Whether the increased technical success is worth the increased time, cost, and payoff uncertainty is a question that is beyond the present study.

The final state attributes are not all equally good as indicators of the differences between the policies and contracts. The differences are most obviously indicated by the payoff, time, and cost attributes of the final states. The fact that the system performance characteristics did not exhibit many significant comparisons may be due to the particular technology used in this study. The percentage uncertainty regarding the system performance characteristics is less than the percentage uncertainty regarding the aerodynamic characteristics at the component level (see Fig. 7). The same phenomenon holds for the gross take-off weight. In the weight case, it is due to the large fixed weight taken by the "other" systems. However, for the fuel economy case, it is due to the whole set of design equations.

Regardless of the reason for the reduction of percentage uncertainty phenomenon, it means that for given variations in technical outcomes at low levels, the percentage variations at higher levels will be less. In view of this, it is not surprising that the system performance characteristics are not strong indicators of the relative superiority of policies or contracts. Of course, this is merely a hypothesis.

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*In some of the preliminary runs, it was observed that the contract with five times the rate of incentive (*NEUT* × 5 in Table 1) did *not* stimulate more search than the low incentive contract. Hence, there may be a threshold phenomenon. This may be worthy of further study.

To examine it would require conducting at least one other study of the same nature as the present study, but with a technology that exhibits increasing uncertainty as one proceeds up through the component-subsystem hierarchy. However, if the hypothesis is true, then more attention should be given to placing incentives on low-level technical characteristics in situations where the uncertainty hierarchy exhibits decreasing percentage uncertainty. This is one of the alternatives suggested in the discussion of extensions below.

REFINEMENTS

There are several features of the model of the system development process used in this study that could be refined to make the model more representative of the real-world process of development. Most of these refinements require significant increases in the size of the computer program. In addition, the decisionmaking policies can be refined in several ways. Six of the more obvious refinements are outlined in this section.

Including Uncertainty About Times and Costs

The times and costs of the various actions in the hypothetical project are constants. This is unrealistic in two respects. First, in certain cases the times and costs of actions will vary with the physical and performance characteristics of the objects of the actions. For example, it seems reasonable that all other things being equal, it should take longer to fabricate a structural member that weighs more than another. Similarly, the equipment and machinery used in the fabrication would be more expensive because it would have to be more substantial. This type of variation in times and costs could be incorporated by expressing the times and costs as some relationship involving the characteristics of the components or subsystems. Uncertainty regarding the times and costs would arise from the uncertainty regarding the characteristics of the components of subsystems.

The second source of variation in times and costs stems from the ability to vary the intensity with which activities are carried out.

By varying the intensity of an activity, it is possible to make tradeoffs between time and cost. In terms of the model of system development used in this study, such variations constitute the definition of alternative actions. For example, the time for a stress analysis for a wing is given in Table 2 as 16 weeks and the cost as $500,000. However, by working overtime or hiring more personnel it may be possible to complete the activity in 12 weeks at a cost of $750,000. Of course, there may also be a change in the precision (as indicated by the coefficient of variation) of the results.

Both of these complications would require improvements in the procedure of forecasting times and costs.

Sequential Versus Parallel Choices

In actual development projects many activities are undertaken at the same time. The model used in this study permits only one activity at a time. Changing the model to permit more than one activity to be undertaken at any one time requires several additional procedures. These procedures are required to evaluate and store the values obtained for all eligible actions at each decision point. Presently, for strictly sequential selection, only the value of the highest value action must be retained. Also, there must be a means of determining how many actions may be undertaken at any one time. To do this, the resources available must be specified. To make the action selections, a scheme for matching the resource requirements of actions with the available resources must be devised for use in conjunction with the schedule of action values. The additional computer memory requirements to implement such a scheme would be very large.

Expanding the Basis of Action Evaluation Beyond the Attributes of the Final State of the Development Process

In many situations the contractor is motivated by more than the attributes of the final state of the development process as defined in this work. Specifically, a strong motivating factor is the possibility of production orders that may follow the development project.

Whether or not there is a follow-on production order (and its size) depends on the final characteristics of the system when development is completed. It should be possible to include some forecast of possible production orders as a function of the attributes of the final state of development and thereby extend the decisionmaking time horizon. Of course, the fact that the present model does not include such a capability should not detract from its usefulness. There are many development situations in which only one complete system is required, or at most a few. These situations are quite prevalent in the space program, where only one satellite of a given type is required.

Incorporating Time Lags in the Information Network

Policy 6 was constructed to demonstrate the effect of not using all the current technical information to make decisions. The situation corresponds to one where decisionmakers have current information regarding only their part of the project. Their information regarding the other parts of the project consists of the initial best estimate. It would perhaps be more realistic to assume a less extreme delay in communication. This could be done by communicating information obtained from actions that precede the most recent action but not from the most recent action itself. It might be useful to examine the implications of delays of various lengths.

Revision of the Definition of Technical Success

Policy 9 was not satisfactory because complete failure was frequent. This could be remedied by revising the definition of technical success each time an assemble and test did not succeed. This would be more consistent with real-world experience. When a development project does not yield the desired results, the contract is sometimes renegotiated, or it may be cancelled if the results are sufficiently bad. This could easily be incorporated in the model used in the present study. All that is needed is a subroutine to redefine the contract in the event of failure. If the cancellation feature is desired, this could be incorporated in the same routine. Cancellation should be based on the results expected from the designs not yet tested rather than the design that just failed.

Catastrophes and Breakthroughs

A very important aspect of system development in the real world is the occurrence of technological breakthroughs and catastrophes. These extremes can be incorporated in the model used in the present research by having four probability distributions. Three of the distributions would correspond to a breakthrough, a catastrophe, and a "normal" outcome. The fourth distribution has three outcomes: one would correspond to a breakthrough, another to a catastrophe, and a third to a normal outcome. The probability of the extreme outcomes would be very low, say, 1 chance in 100, and the normal outcome would have a high probability of occurrence, say, 98 chances in 100. Each time an action that may lead to a breakthrough or catastrophe is executed, the fourth distribution would be sampled. Then, depending on the outcome, one of three other distributions would be sampled to determine the value of the outcome. This procedure would be useful only if there was some basis for anticipating catastrophes and breakthroughs for given actions.

EXTENSIONS

There are many ways in which the present work can be extended. The most obvious extension is to similar studies involving other technologies or different decisionmaking policies. One interesting policy variation is the "compound" policy. A compound policy consists of several simple policies, such as those examined in this study, that are used for decisionmaking at different times during a development project. It seems logical that the importance of the various aspects of the system and the project may vary as the program progresses. Hence, it might be advantageous to vary the decisionmaking policy used when there is a change in the conditions under which the program is being conducted. An example of such changes in conditions is a technological catastrophe or breakthrough.

A great deal of additional work can be done in the area of multiple incentive contracts using the methods developed in this research. The inclusion of two contracts in the present study was only intended to demonstrate the usefulness of the methods for such analysis. Some of the interesting aspects of incentive contracting that can be studied include the effect of placing incentives at different levels of the technical hierarchy, e.g., placing incentives on $C_{D_f}S$ instead of *NMI/LB*.

Another variation is the effect of placing incentives on the times of various events during development--e.g., first static test, or first flight test--as opposed to having only one incentive on the final delivery date.*

Perhaps the most interesting and valuable extension of the present work is related to the question of allocation of resources between research activities and development activities. The distinction between the two aspects of the state of knowledge in system development makes this extension possible. The design equations are almost never known with precise certainty. In many cases, the amount of uncertainty regarding these equations is sufficiently small that it can be safely neglected. However, in many other cases the uncertainty regarding the equations cannot, or at least should not, be ignored. The uncertainty can take two forms: (1) regarding the numerical constants in the equations--the coefficients and exponents; and (2) regarding the analytical form of the equations themselves. Using the methods described in this study, it should be possible to analyze whether uncertainty about the component characteristics or uncertainty about the relationships between the characteristics contribute more to the total uncertainty regarding the ultimate performance of the system. This information could be used as the basis for allocating resources to acquiring more information about the components--development--or allocating resources toward improving the knowledge regarding the design equations--research.

An extension of the present work that has a more immediate application is the area of cost estimating. A cost-estimating relationship is a functional relationship between the characteristics of a system or piece of equipment and its cost. Hence, the methods developed in

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*Rule 1 of Klein, et al., implies that the fewer the restrictions, the better the expected results. However, multiple time incentives are common practice.

this study can be used to generate probabilistic cost estimates during the course of development of a system or piece of equipment.

Another interesting area in which the present work might be useful is in teaching classes on policies for decisionmaking. There are several possibilities. The students could be supplied with a list of programmed policies and they would make their choices from the list. Another possibility is to let the students devise their own policies and write subroutines to use these programs.* Of course, the students could make their own choices without the use of programmed policies. Or, they could play against a programmed policy.

A new scheme for contract negotiation might be established using the information generated by the simulation of project histories. The results obtained in the present work yield a good example. The results shown in Table 5 (page 60) can be viewed as the outcomes under a two-person, non-zero-sum game. One player is the customer whose choices are the contracts, and the other player is the contractor whose choices are the decisionmaking policies. The results of contract negotiation would specify the contract and the decisionmaking policy to be used for the development.

A very interesting related study would be to have several project engineers select actions using the hypothetical project described in this study and compare their results to the results obtained here. The value of such a study would be greatly enhanced by interviewing the engineers to determine how they arrived at their decisions.

The suggestion of using experienced engineers to study decisionmaking methods raises the question of using the methods developed in this study in real-world situations. While, at this time, it would be impractical to use any of the decisionmaking policies studied in this research as the basis for making real-world decisions, the information structure might be very useful. At present, sensitivity analysis is used to determine the extent of variation in system performance for given variations in component characteristics. The information system described in this study is a risk analysis system and would enhance the value of such sensitivity information because it would show not only the amount of variation in system performance, but it would also give information on how likely such variations would be.

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*As will be shown in Appendix C, only five routine changes, at most, are necessary to change the policy.

Appendix A

AIRCRAFT FUEL ECONOMY PERFORMANCE

This Appendix presents the derivations of the expressions for the fuel economy performance of the aircraft for the mission profile shown in Sec. I of this study.

AIRCRAFT PERFORMANCE*

Level flight of the aircraft at a constant speed requires that the total thrust, T, equals the total drag, D,

$$T = D, \tag{34}$$

and that the lift, L, equals the instantaneous gross weight, W,

$$L = W. \tag{35}$$

The drag, in pounds, can be expressed in terms of the speed of the aircraft in knots, V, the wing area in square feet, S, the altitude density ratio, σ, and the drag coefficient C_D, as

$$D = \frac{\sigma S V^2}{294.8} C_D. \tag{36}$$

Using the parabolic polar form for the drag coefficient,

$$C_D = C_{D_f} + \frac{C_L}{\pi \mathit{AR}\, e}, \tag{37}$$

the thrust, which equals the drag by Eq. (34), can be expressed as

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*The material under this subheading is basic aerodynamic theory of sub-sonic, level flight. For a more detailed exposition the reader is referred to Courtland D. Perkins and Robert E. Hage, op. cit., pp. 1-97.

$$T = \frac{\sigma S V^2}{294.8}\left(C_{D_f} + \frac{C_L^2}{\pi \text{Æ} e}\right), \tag{38}$$

where C_{D_f} = the coefficient of frictional drag,

C_L = the lift coefficient,

Æ = the aspect ratio of the wing,

e = the airplane efficiency factor,

π = 3.14159... .

There is an expression similar to Eq. (36) for the lift and the lift coefficient. Combining this with Eq. (35) gives

$$C_L = \frac{294.8W}{\sigma S V^2}. \tag{39}$$

The thrust, in pounds, that is required for level flight at speed V and at an altitude corresponding to σ is found by substituting (39) into (38)

$$T = \frac{\sigma S V_t^2}{294.8}\left[C_{D_f} + \frac{1}{\pi \text{Æ} e}\left(\frac{294.8W}{\sigma S V^2}\right)^2\right]. \tag{40}$$

To change pounds of thrust to horsepower, the thrust is multiplied by the speed in knots and divided by 325.6. Hence, the thrust horsepower required, THP_R, is given by

$$THP_R = \frac{\sigma S V^3}{325.6 \times 294.8}\left[C_{D_f} + \frac{1}{\pi \text{Æ} e}\left(\frac{294.8W}{\sigma S V^2}\right)^2\right]. \tag{41}$$

ENGINE PERFORMANCE*

The expression for the thrust horsepower available per engine is embodied in a set of instructions for calculating the engine performance on pages 38-40 of the Allison Model Specification for the T56-A-10W/10WA Engine.† In addition, an equation for the fuel flow is necessary. Following is a list of symbols that will be used in these equations:

η_P = propeller efficiency (%).

η_D = duct efficiency (%).

p_{s7} = engine outlet static pressure (In. Hg Abs).

p_{am} = ambient pressure (In. Hg Abs).

p_o = sea-level pressure (In. Hg Abs).

RTR = ram temperature ratio.

RPR = ram pressure ratio.

SHP = shaft horsepower.

δ = p_{t2}/p_o.

ΔSHP = change in SHP.

K_2 = ram correction for shaft horsepower.

T_{t2} = compressor inlet temperature (°F).

T_{t5} = turbine inlet temperature (°F).

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*The material contained under this subheading is taken from *Model Specification No. 479-D, Navy Model T56-A-10W/10WA*, Allison Division of General Motors Corp., Indianapolis, Indiana, 2 November 1964. The symbols are the same as used by Allison.

†Ibid.

T_{am} = ambient temperature (°R).

HPE = horsepower extracted.

V = airspeed (knots).

F_g = gross thrust (lb)

K_1 = ram correction for F_g.

w_a = air flow (lb/sec).

w_f = fuel flow (lb/hr).

The thrust horsepower available per engine is given by

$$THP_A = \frac{\eta_p \eta_D p_{s7} p_{am} RTR^{3.5}}{p_o}$$

$$\times \left[\left(\frac{SHP}{\delta}\right)_{16} + \left(\frac{\Delta SHP}{\delta K_2 \sqrt{T_{t2}}}\right)_{17} (K_2)_{17} \sqrt{T_{am}} RTR - \frac{HPEp_o}{\eta_D p_{s7} p_{am} RTR^{3.5}}\right]$$

$$+ \frac{Vp_{s7}\eta_D p_{am} RTR^{3.5}}{325.6 p_o} \left[\left(\frac{F_g}{K_1}\right)_{14} (K_1)_{14} - \frac{V}{19.06}\left(\frac{w_a}{\delta}\right)_{15}\right]. \qquad (42)$$

The quantities in parentheses with subscripts that run from 14 to 17 refer to engine performance items that are presented as graphs in the model specification.* The numerical subscripts correspond to the number of the figure in the model specification. In order to proceed with the propagation of error technique, it is necessary to express the quantities from Figs. 14-17 in that publication in analytical form. Figure 14 shows $F_g/\delta K_1$ as a function of T_{t2} and T_{t5}. It also shows

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*Ibid.

K_1 as a function of *RPR*. Figure 15 shows w_a/δ as a function of T_{t2} and T_{t5}. Figure 17 shows $\Delta SHP/K_2\delta\sqrt{T_{t2}}$ as a function of T_{t2}, T_{t5}, and *RPR*. It also shows K_2 as a function of T_{t2} and T_{t5}.

The compressor inlet temperature, T_{t2}, can be expressed as

$$T_{t2} = T_{am} + 2.369 \times 10^{-4}V^2 - 459.7, \qquad (43)$$

and the ram temperature ratio can be expressed as

$$RTR = 1 + 2.369 \times 10^{-4}V^2/T_{am}. \qquad (44)$$

Hence, all the quantities in Figs. 14-17 can be written as functions of V, T_{t5}, and the atmospheric constants. Furthermore, δ can be written as a function of V and the atmospheric constants. Consequently, Eq. (42) can be written as a function of V, T_{t5}, and the atmospheric constants.

The equations for the quantities in Figs. 14-17 were obtained by determining the range of values of the independent variables for which a fit was desired, selecting a form for the equation, reading a set of points off the graph, and making a least-squares fit. For most of the curves a linear approximation appeared reasonable over limited ranges of the independent variables. Because the aircraft performance is of interest at an airspeed of 200 knots, it is necessary to fit the curve only for a short range, about T_{t2}, corresponding to V = 200 knots and T_{am} = 513.4°*R*. The resultant equations are:

$$K_1 = .1621 + .9145RPR - .0763RPR^2. \qquad (45)$$

$$\frac{F_g}{\delta K_1} = 236.24 - .72T_{t2} + .3764T_{t5} - .0012T_{t2}T_{t5}. \qquad (46)$$

$$\frac{w_a}{\delta} = 36.51 - .0707T_{t2}. \tag{47}$$

$$\frac{SHP}{\delta} = -4574.4 + 8.2T_{t2} + 5.238T_{t5} - .014T_{t2}T_{t5}. \tag{48}$$

$$K_2 = 1.175 - .0004T_{t2} + .00011T_{t5}. \tag{49}$$

$$\begin{aligned} \frac{\Delta SHP}{\delta K_2\sqrt{T_{t2}}} = {} & 107.4 - 104.45\left(\frac{T_{t5}+459.7}{T_{t2}+459.7}\right) - 105.44RPR \\ & + 103.01RPR\left(\frac{T_{t5}+459.7}{T_{t2}+459.7}\right) + 12.44\left(\frac{T_{t5}+459.7}{T_{t2}+459.7}\right)^2 \\ & - 12.15RPR\left(\frac{T_{t5}+459.7}{T_{t2}+459.7}\right)^2. \end{aligned} \tag{50}$$

The equation for the fuel flow is determined from Fig. 18 of the model specification. The result is

$$\frac{w_f}{\delta} = -1011.42 - 2.450T_{t2} + 2.00T_{t5} - .0053T_{t2}T_{t5}. \tag{51}$$

SYSTEM PERFORMANCE

The number of nautical miles traveled per pound of fuel consumed, NMI/LB, is found by dividing the airspeed (in knots) by the fuel flow (in pounds per hour). If w_f is the fuel flow for one engine, then Nw_f is the fuel flow for N engines. Equation (51) gives w_f/δ; hence, NMI/LB can be expressed as

$$\frac{NMI}{LB} = \frac{V}{N\delta\left(\frac{w_f}{\delta}\right)} \tag{52}$$

and δ is given by

$$\delta = \frac{p_{t2}}{p_o},$$

$$\delta = \frac{\eta_D p_{am} p_{s7} RTR^{3.5}}{p_o}. \tag{53}$$

RTR is given by Eq. (44) and w_f/δ by Eq. (51). Hence, to determine NMI/LB, it is necessary to know T_{t5}. All other quantities are known characteristics of the engines or the flight conditions.

To determine an expression for T_{t5},* the thrust horsepower required is set equal to the thrust horsepower available from all operating engines.

$$THP_R = N \times THP_A. \tag{54}$$

Making all the necessary substitutions, measuring all temperatures in degrees Rankine,† and solving for T_{t5} yields the following cubic equation:

$$k_3(T_{t5}{}^\circ R)^3 + k_2(T_{t5}{}^\circ R)^2 + k_1 T_{t5}{}^\circ R + k_0 = 0 \tag{55}$$

where

$$k_3 = \eta_p \delta C_3(B_6 + B_7 RPR + B_9 RPR^2)/(T_{t2}{}^\circ R)^{\frac{3}{2}}, \tag{56}$$

$$k_2 = \eta_p \delta \Big((B_6 + B_7 RPR + B_9 RPR^2)\Big\{[C_1/(T_{t2}{}^\circ R)^{\frac{3}{2}}]$$
$$+ [C_2/(T_{t2}{}^\circ R)^{\frac{1}{2}}]\Big\} + (B_2 + B_4 RPR + B_8 RPR^2)(C_3/T_{t2}{}^\circ R)^{\frac{1}{2}})\Big), \tag{57}$$

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*The turbine inlet temperature, T_{t5}, corresponds to the engine power setting. As the power level varies, T_{t5} varies. See Figs. 34 and 35 of the model specification, Ibid.

†Temperature in degrees Rankine equals temperature in degrees Fahrenheit plus 459.7.

$$k_1 = \eta_p\delta \left\{(A_3 + A_4T_{t2}{}^\circ R) + (T_{t2}{}^\circ R)^{\frac{1}{2}} \Big|(B_2 + B_4RPR + B_8RPR^2)\right.$$

$$\left.\times [C_2 + C_1/(T_{t2}{}^\circ R)] + C_3(B_1 + B_3RPR + B_5RPR^2)\Big|\right\} + \frac{V\delta}{325.6}$$

$$\times (E_1 + E_2RPR + E_3RPR^2)(D_3 + D_4T_{t2}{}^\circ R), \tag{58}$$

$$k_0 = \eta_p\delta \Big|A_1 + A_2T_{t2}{}^\circ R + (T_{t2}{}^\circ R)^{\frac{1}{2}}(B_1 + B_3RPR + B_5RPR^2)$$

$$\times (C_1 + C_2T_{t2}{}^\circ R)\Big| + \frac{V\delta}{325.6}\Big|(E_1 + E_2RPR + E_3RPR^2)$$

$$\times (D_1 + D_2T_{t2}{}^\circ R) - \frac{V}{19.06}(F_1 + F_2T_{t2}{}^\circ R)\Big| - \eta_p HPE$$

$$- \frac{\sigma SV^3}{325.6 \times 294.8W}\left|C_{D_f} + \frac{1}{\pi\, AR\, e}\left(\frac{294.8W}{\sigma SV^2}\right)^2\right|, \tag{59}$$

and

$$A_1 = -4574.4 - 459.7(8.2 + 5.238) + 459.7^2(-.014), \tag{60}$$

$$A_2 = 8.2 - 459.7(-.014), \tag{61}$$

$$A_3 = 5.238 - 459.7(-.014), \tag{62}$$

$$A_4 = -.014, \tag{63}$$

$$B_1 = -35.05, \tag{64}$$

$$B_2 = 14.02, \tag{65}$$

$$B_3 = 151.33, \tag{66}$$

$$B_4 = -110.18, \tag{67}$$

$$B_5 = -116.12, \tag{68}$$

$$B_6 = -14.77, \tag{69}$$

$$B_7 = 36.81, \tag{70}$$

$$B_8 = 96.08, \tag{71}$$

$$B_9 = -22.03, \tag{72}$$

$$C_1 = 1.175 - 459.7(-.0004 - .00011), \tag{73}$$

$$C_2 = -.0004, \tag{74}$$

$$C_3 = -.00011, \tag{75}$$

$$D_1 = 236.24 - 459.7(-.72 + .3764) + 459.7^2(-.0012), \tag{76}$$

$$D_2 = -.72 - 459.7(-.0012), \tag{77}$$

$$D_3 = .3764 - 459.7(-.0012), \tag{78}$$

$$D_4 = -.0012, \tag{79}$$

$$E_1 = .1621, \tag{80}$$

$$E_2 = .9145, \tag{81}$$

$$E_3 = -.0763. \tag{82}$$

The accuracy of these equations in determining the various engine performance items and the fuel economy figure was determined by comparing the results of several calculations obtained using the equations to the results obtained using the procedure described in the model specification for the same sets of conditions. In all cases, the discrepancy was less than 10 percent, so the equations were considered to be sufficiently accurate for the purposes of this study.

For the computer program, a further simplification was made. It was observed in the accuracy checks that the cubic term of Eq. (55) made a contribution of the order of 1 percent to the results. For many of the accuracy check cases, this was much less than the discrepancy; consequently, the cubic term was dropped in order to simplify the calculations. The resulting equation is

$$k_2(T_{t5}\,^\circ R)^2 + k_1 T_{t5}\,^\circ R + k_0 - \frac{\sigma S V^3}{325.6 \times 294.8W} \times \left[C_{D_f} + \frac{1}{\pi\, \mathit{AR}\, e}\left(\frac{294.8W}{\sigma S V^2}\right)^2\right] = 0. \tag{83}$$

Appendix B

DERIVATIONS

PROPAGATION OF UNCERTAINTY EXPRESSIONS

This section of Appendix B will present the expressions used in the propagation of uncertainty calculations. They will be organized according to the hierarchy of design equations as shown in Fig. 4.

Airframe Weight

The airframe weight, W_A, is the sum of the weights of the two major structures members, the wing and nacelles, W_w, and the fuselage and tail, W_F.

$$W_A = W_w + W_F. \tag{84}$$

Hence, the propagation of uncertainty yields

$$E(W_A) = E(W_w) + E(W_F) \tag{85}$$

and

$$\sigma^2(W_A) = \sigma^2(W_w) + \sigma^2(W_F). \tag{86}$$

Airframe Airplane Efficiency Factor

The airplane efficiency factor at the airframe level, e_A, is the same as at the wing level, e_w. Hence,

$$e_A = e_w. \tag{87}$$

The propagation of uncertainty yields

$$E(e_A) = E(e_w), \tag{88}$$

$$\sigma^2(e_A) = \sigma^2(e_w). \tag{89}$$

Airframe Frictional Drag Coefficient

In this research, it has been assumed that the frictional drag coefficient of the airframe, $C_{D_f A}$, is equal to the sum of the frictional drag coefficient of the wings, $C_{D_f w}$, plus the frictional drag coefficient of the fuselage and tail, $C_{D_f F}$. In reality, a very large compcnent of the frictional drag is generated by interference between the fuselage and the wings. As the hypothetical project was set up for this study, the fuselage included a sufficient stub of the wing to account for the interference without including any drag due to the wing itself. Hence, the frictional drag coefficient for the fuselage and tail includes the interference. This simplifies the equations and measurement problem. Hence,

$$C_{D_f A} = C_{D_f F} + C_{D_f w} \tag{90}$$

and the propagation of uncertainty gives

$$E(C_{D_f A}) = E(C_{D_f F}) + E(C_{D_f w}), \tag{91}$$

$$\sigma^2(C_{D_f A}) = \sigma^2(C_{D_f F}) + \sigma^2(C_{D_f w}). \tag{92}$$

Aircraft Gross Take-off Weight

The gross take-off weight of the aircraft, $GTO\ WT$, is the sum of the weights of the engines, W_E, the airframe, W_A, and the other subsystems that make up the "flight-ready" aircraft, W_O. Hence,

$$GTO\ WT = W_E + W_A + W_O \tag{93}$$

and the propagation of uncertainty gives

$$E(GTO\ WT) = E(W_E) + E(W_A) + E(W_O), \tag{94}$$

$$\sigma^2(GTO\ WT) = \sigma^2(W_E) + \sigma^2(W_A) + \sigma^2(W_O). \tag{95}$$

Aircraft Airplane Efficiency Factor

Because the efficiency factor is the same at all levels, the efficiency factor at the aircraft, or system, level, e_S, is the same as at the airframe level, e_A. Therefore,

$$e_S = e_A. \tag{96}$$

Hence, the propagation of uncertainty yields

$$E(e_S) = E(e_A), \tag{97}$$

$$\sigma^2(e_S) = \sigma^2(e_A). \tag{98}$$

Aircraft Frictional Drag Coefficient

The frictional drag coefficient at the aircraft level, $C_{D_f S}$, is the same as at the airframe level, $C_{D_f A}$.* Hence,

$$C_{D_f S} = C_{D_f A} \tag{99}$$

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*This is for the aircraft in a "clean" configuration; e.g., landing gear up, etc. As two of the engines are shut down for the mission that is the basis of all of these calculations, there is an increase in the drag due to the two feathered propellers. A reasonable value of the increase in C_{D_f} for this type of aircraft is .003. In this study the increment is assumed to be present in all designs and it is included in the drag coefficient for the wings.

and the propagation of uncertainty gives

$$E(C_{D_fS}) = E(C_{D_fA}), \tag{100}$$

$$\sigma^2(C_{D_fS}) = \sigma^2(C_{D_fA}). \tag{101}$$

Aircraft Fuel Economy

The aircraft fuel economy, *NMI/LB*, is a function of the performance of the engines and the aerodynamic characteristics of the aircraft. The latter are determined as described above. The performance of the engines was discussed in Appendix A.

Rewriting Eq. (83) in terms of THP_R and N gives

$$k_2(T_{t5}{}^\circ R)^2 + k_1T_{t5}{}^\circ R + k_0 - \frac{THP_R}{N} = 0. \tag{102}$$

Solving this for $T_{t5}{}^\circ R$ yields

$$T_{t5}{}^\circ R = \frac{-k_1}{2k_2} \pm \frac{\left[k_1^2 - 4k_2\left(k_0 - \frac{THP_R}{N}\right)\right]^{\frac{1}{2}}}{2k_2}. \tag{103}$$

Denote the value of $T_{t5}{}^\circ R$ obtained from Eq. (103) with the plus sign* and converted to degrees Fahrenheit by T^*_{t5}. Then Eq. (52) for *NMI/LB* can be written as

$$\frac{NMI}{LB} = \frac{V/N\delta}{-1011.42 - 2.450T_{t2} + 2.00T^*_{t5} - .0053T_{t2}T^*_{t5}}, \tag{104}$$

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*The turbine inlet temperature can never be zero on the Rankine scale; hence, because the ratio of k_1/k_2 is always positive, the first term of Eq. (85) is always negative and the plus sign must be chosen to obtain a positive $T_{t5}{}^\circ R$.

where T_{t2} is given by Eq. (43), and δ is given by Eq. (53).

The expression for THP_R contains the aerodynamic characteristics of the aircraft: $C_{D_f S}$ and e_S. These are the only sources of uncertainty in Eq. (104) as the example in this research is set up. Given normal probability distributions for $C_{D_f S}$ and e_S, with means $E(C_{D_f S})$ and $E(e_S)$, and standard deviations $\sigma(C_{D_f S})$ and $\sigma(e_S)$, the probability distribution for NMI/LB is given by $E(NMI/LB)$ and $\sigma(NMI/LB)$ with $E(NMI/LB)$ calculated using Eq. (104) with $E(C_{D_f S})$ and $E(e_S)$ used in the expression for THP_R, and

$$\sigma(NMI/LB) = \left\{\left[\frac{\partial\left(\frac{NMI}{LB}\right)}{\partial C_{D_f S}}\right]^2 \sigma^2(C_{D_f S}) + \left[\frac{\partial\left(\frac{NMI}{LB}\right)}{\partial e_S}\right]^2 \sigma^2(e_S)\right\}^{\frac{1}{2}} . \qquad (105)$$

Differentiating Eq. (104) to determine the partial derivatives in Eq. (105) is far more involved than using the chain rule and starting with Eq. (52). Following the latter course of action yields

$$\frac{\partial\left(\frac{NMI}{LB}\right)}{\partial C_{D_f S}} = \frac{\partial}{\partial C_{D_f S}}\left[\frac{V}{N\delta\left(\frac{w_f}{\delta}\right)}\right]$$

$$= \frac{-V}{N\delta}\,\frac{\dfrac{\partial\left(\frac{w_f}{\delta}\right)}{\partial C_{D_f S}}}{\left(\frac{w_f}{\delta}\right)^2}, \qquad (106)$$

$$\frac{\partial\left(\frac{w_f}{\delta}\right)}{\partial C_{D_f}S} = \frac{\partial}{\partial C_{D_f}S} \left(-1924.573 - .01359T_{t2} + 4.43641T_{t5} - .0053T_{t2}T_{t5}\right)$$

$$= \left(4.43641 - .0053T_{t2}\right) \frac{\partial T_{t5}}{\partial C_{D_f}S}, \tag{107}$$

$$\frac{\partial T_{t5}}{\partial C_{D_f}S} = \frac{\partial}{\partial C_{D_f}S} \left[\frac{-k_1 + \left(k_1^2 - 4k_2k_0 + 4k_2THP_R/N\right)^{\frac{1}{2}}}{2k_2}\right]$$

$$= \left(k_1^2 - 4k_2k_0 + 4k_2THP_R/N\right)^{-\frac{1}{2}} \frac{1}{N} \frac{\partial THP_R}{\partial C_{D_f}S}, \tag{108}$$

$$\frac{\partial THP_R}{\partial C_{D_f}S} = \frac{\partial}{\partial C_{D_f}S} \left\{\frac{\sigma SV^3}{325.6 \times 294.8} \left[C_{D_f} + \frac{1}{\pi \, AR \, e_S} \left(\frac{294.8W}{\sigma SV^2}\right)^2\right]\right\}$$

$$= \frac{\sigma SV^3}{325.6 \times 294.8}. \tag{109}$$

Combining Eqs. (109), (108), (107), and (106) yields

$$\frac{\partial\left(\frac{NMI}{LB}\right)}{\partial C_{D_f}S} = -\frac{V}{N\delta\left(\frac{w_f}{\delta}\right)^2} \left(4.4361 - .0053T_{t2}\right)$$

$$\times \left[\frac{\left(k_1^2 - 4k_2k_0 + 4k_2THP_R/N\right)^{-\frac{1}{2}}}{N}\right] \frac{\sigma SV^3}{325.6 \times 294.8}. \tag{110}$$

Similarly,

$$\frac{\partial\left(\frac{NMI}{LB}\right)}{\partial e_S} = \frac{V}{N\delta\left(\frac{w_f}{\delta}\right)} \left(4.4361 - .0053T_{t2}\right)$$

$$\times \left[\frac{(k_1^2 - 4k_2k_0 + 4k_2THP_R/N)^{-\frac{1}{2}}}{N} \right] \frac{294.8W^2}{325.6\pi \; AR \; e_S^2 \sigma SV}. \qquad (111)$$

In both Eqs. (110) and (111), THP_R is evaluated at $E(C_{D_{f}S})$ and $E(e_S)$.

DERIVATION OF EXPECTED PAYOFF FOR PERFORMANCE INCENTIVES

The expressions for the expected payoffs for the two system performance characteristics that are included in the multiple incentive contract are quite similar. They differ only because the direction of the penalties and rewards are reversed. The basic expression for both expected payoffs will be presented, but the derivation will be carried through for only one.

For both performance characteristics, the expected payoff has two segments: the expectation over rewards for superior performance and the expectation over penalties for inferior performance. Consider the fuel economy performance. Let x denote a particular value of NMI/LB, let μ denote $E(NMI/LB)$, and let σ denote $\sigma(NMI/LB)$. Then

$$\begin{aligned} EPANMI = {} & RPSNMI \int_{PSRNMI}^{\infty} \frac{(x - PSRNMI)}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] dx \\ & - CPSNMI \int_{-\infty}^{PSRNMI} \frac{(PSRNMI - x)}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] dx. \end{aligned} \qquad (112)$$

Similarly for $GTO\ WT$:

$$\begin{aligned} EPAGTO = {} & RPSGTO \int_{-\infty}^{PSRGTO} \frac{(PSRGTO - x)}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] dx \\ & - CPSGTO \int_{PSRGTO}^{\infty} \frac{(x - PSRGTO)}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] dx, \end{aligned} \qquad (113)$$

where x, μ, and σ in Eq. (113) refer to *GTO WT*.

Proceeding with Eq. (112), let

$$y = (x - \mu)/\sigma. \tag{114}$$

Then

$$x = \sigma y + \mu, \tag{115}$$

$$dx = \sigma\, dy, \tag{116}$$

and when $x = PSRNMI$,

$$y = (PSRNMI - \mu)/\sigma.$$

Making these substitutions into Eq. (112) yields

$$\begin{aligned} EPANMI = {} & RPSNMI \int_{(PSRNMI-\mu)/\sigma}^{\infty} \frac{(\sigma y + \mu - PSRNMI)}{\sqrt{2\pi}\,\sigma} \exp\left(-\frac{y^2}{2}\right) \sigma\, dy \\ & - CPSNMI \int_{-\infty}^{(PSRNMI-\mu)/\sigma} \frac{(PSRNMI - \sigma y - \mu)}{\sqrt{2\pi}} \exp\left(-\frac{y^2}{2}\right) \sigma\, dy. \end{aligned} \tag{117}$$

Expanding the parentheses within the integrals and collecting some terms yields

$$\begin{aligned} EPANMI = {} & \frac{RPSNMI}{\sqrt{2\pi}} \int_{(PSRNMI-\mu)/\sigma}^{\infty} y \exp\left(-\frac{y^2}{2}\right) dy \\ & + \frac{\sigma CPSNMI}{\sqrt{2\pi}} \int_{-\infty}^{(PSRNMI-\mu)/\sigma} y \exp\left(-\frac{y^2}{2}\right) dy \\ & + \frac{RPSNMI(\mu - PSRNMI)}{\sqrt{2\pi}} \int_{(PSRNMI-\mu)/\sigma}^{\infty} \exp\left(-\frac{y^2}{2}\right) dy \\ & - \frac{CPSNMI(PSRNMI - \mu)}{\sqrt{2\pi}} \int_{-\infty}^{(PSRNMI-\mu)/\sigma} \exp\left(-\frac{y^2}{2}\right) dy. \end{aligned} \tag{118}$$

It should be recognized that

$$\frac{\exp\,(-y^2/2)}{\sqrt{2\pi}} = f(y) \tag{119}$$

is the normal density function with zero mean and unit variance. Also, $y \exp\,(-y^2/2)\, dy$ is the exact differential of $-\exp\,(-y^2/2)$. Hence, Eq. (118) can be rewritten as

$$\begin{aligned} EPANMI = {} & \frac{\sigma RPSNMI}{\sqrt{2\pi}} \left[\exp\left(-\frac{y^2}{2}\right) \Bigg|_{(PSRNMI-\mu)/\sigma}^{\infty} \right] + \frac{\sigma CPSNMI}{\sqrt{2\pi}} \\ & \times \left[-\exp\left(-\frac{y^2}{2}\right) \Bigg|_{-\infty}^{(PSRNMI-\mu)/\sigma} \right] + RPSNMI(\mu - PSRNMI) \\ & \times \int_{(PSRNMI-\mu)/\sigma}^{\infty} \frac{\exp\,(-y^2/2)}{\sqrt{2\pi}}\, dy - CPSNMI(PSRNMI - \mu) \\ & \times \left[1 - \int_{(PSRNMI-\mu)/\sigma}^{\infty} \exp\left(-\frac{y^2}{2}\right) dy \right]. \end{aligned} \tag{120}$$

Now it should be noticed that

$$\frac{2}{\sqrt{\pi}} \int_z^{\infty} \exp\,(-v^2)\, dv = ERFC(z) \tag{121}$$

is the complementary error function of z. Hence, let

$$\frac{y^2}{2} = v^2. \tag{122}$$

Then

$$y = \sqrt{2}\, v, \tag{123}$$

$$dy = \sqrt{2}\ dv \tag{124}$$

and when $y = (PSRNMI - \mu)/\sigma$, $v = (PSRNMI - \mu)/\sqrt{2}\ \sigma$. Also note that the lower limit of the second integral has no meaning in reality; hence, it is replaced by zero. Now Eq. (120) can be rewritten as

$$EPANMI = \frac{\sigma RPSNMI}{\sqrt{2\pi}} \exp\left[-\frac{(PSRNMI-\mu)^2}{\sigma^2}\right] - \frac{\sigma CPSNMI}{\sqrt{2\pi}} \exp\left[-\frac{(PSRNMI-\mu)^2}{\sigma^2}\right]$$
$$+ \frac{\sigma CPSNMI}{\sqrt{2\pi}} + \frac{(RPSNMI - CPSNMI)(\mu - PSRNMI)}{2} ERFC\left(\frac{PSRNMI - \mu}{\sqrt{2}\sigma}\right)$$
$$- CPSNMI(PSRNMI - \mu). \tag{125}$$

The expression for *EPAGTO* is derived similarly beginning with Eq. (113). The result is

$$EPAGTO = \frac{\sigma(CPSGTO - RPSGTO)}{\sqrt{2\pi}} \exp\left[-\frac{(PSRGTO-\mu)^2}{\sigma^2}\right]$$
$$- RPSGTO\left(\mu - PSRGTO + \frac{\sigma}{\sqrt{2\pi}}\right)$$
$$- \frac{(CPSGTO - RPSGTO)(PSRGTO - \mu)}{2} ERFC\left(\frac{PSRGTO - \mu}{\sqrt{2}\sigma}\right). \tag{126}$$

DERIVATION OF THE PROBABILITY OF TECHNICAL SUCCESS

Technical success is defined as both system performance factors being equal or superior to the zero performance incentive payoff levels. Specifically, technical success occurs when

$$\frac{NMI}{LB} \geq PSRNMI, \tag{127}$$

and

$$GTO\ WT \leq PSRGTO. \tag{128}$$

Because these two technical performance factors are independent, the probability that both Eq. (127) and Eq. (128) will be jointly satisfied is given by the product of the probabilities that they will be independently satisfied. Hence,

$$Pr\left(\frac{NMI}{LB} \geq PSRNMI,\ GTO\ WT \leq PSRGTO\right) = Pr\left(\frac{NMI}{LB} \geq PSRNMI\right) \times Pr(GTO\ WT \leq PSRGTO). \tag{129}$$

Probability That Fuel Economy Exceeds *PSRNMI*

Let

$$x = NMI/LB, \tag{130}$$

$$\mu = E(NMI/LB), \tag{131}$$

$$\sigma = \sigma(NMI/LB). \tag{132}$$

Then

$$Pr\left(\frac{NMI}{LB} \geq PSRNMI\right) = \frac{1}{\sqrt{2\pi}\ \sigma} \int_{PSRNMI}^{\infty} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] dx. \tag{133}$$

Making the substitutions shown in Eqs. (114), (115), and (116) gives

$$Pr\left(\frac{NMI}{LB} \geq PSRNMI\right) = \frac{1}{\sqrt{2\pi}} \int_{(PSRNMI-\mu)/\sigma}^{\infty} \exp\left(-\frac{y^2}{2}\right) dy. \tag{134}$$

Again, recognizing Eq. (121) and making the substitutions shown in Eqs. (122), (123), and (124) yields

$$Pr\left(\frac{NMI}{LB} \geq PSRNMI\right) = \frac{1}{2}\ ERFC\left(\frac{PSRNMI - \mu}{\sqrt{2}\ \sigma}\right). \tag{135}$$

Probability That Gross Take-off Weight Is Less Than *PSRGTO*

Proceeding similarly to the above,

$$Pr(GTO\ WT \le PSRGTO) = \frac{1}{\sqrt{2\pi}\ \sigma} \int_{\infty}^{PSRGTO} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] dx \qquad (136)$$

becomes

$$Pr(GTO\ WT \le PSRGTO) = 1 - \frac{1}{2}\ ERFC\left(\frac{PSRGTO - \mu}{\sqrt{2}\ \sigma}\right). \qquad (137)$$

Appendix C

DESCRIPTION OF THE COMPUTER PROGRAM

The computer program used in this study was written in FORTRAN IV. All runs were made on an IBM 360/40 at The Rand Corporation. Reproduction of the program listings is not feasible as this would require approximately 70 pages. Instead, the functions the subroutines perform will be discussed briefly. Figure 14 shows the

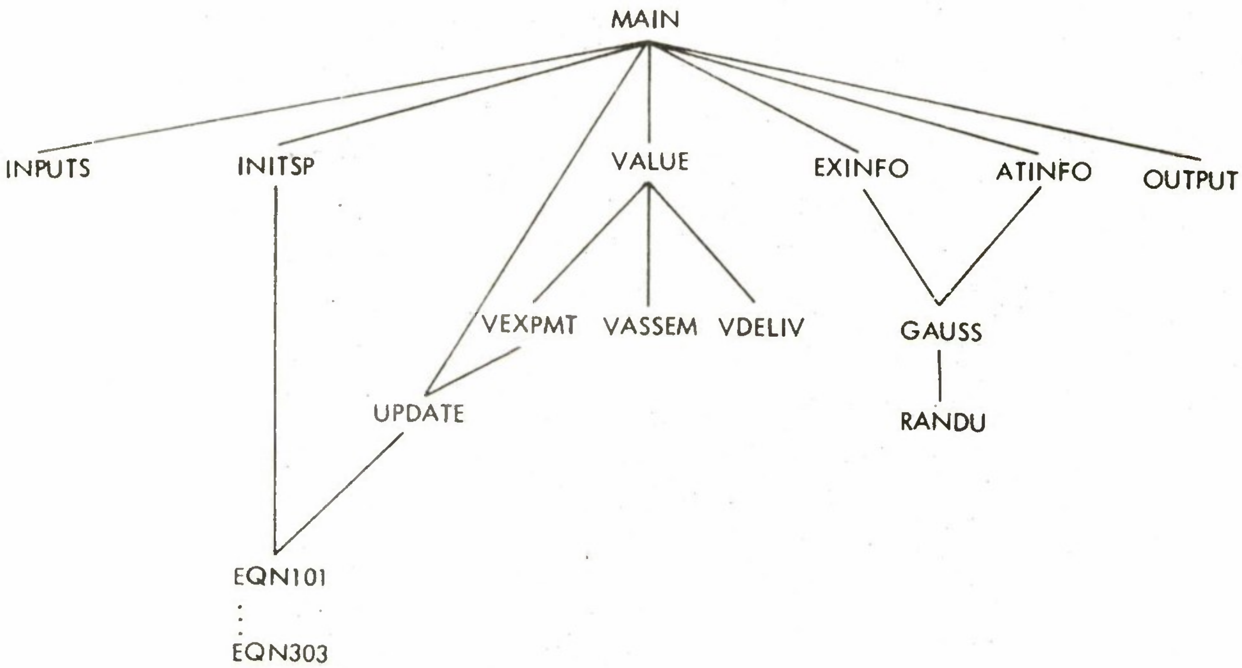

Fig. 14--Calling hierarchy

relationships of the subroutines through the calling statements. To change the decisionmaking policy, only the MAIN, VALUE, VEXPMT, VASSEM, and VDELIV subroutines need to be changed. Some changes do not require all these subroutines to be changed.

MAIN PROGRAM

The main program performs a large portion of the bookkeeping tasks including: (1) initializing the time, cost, sequence numbers, probability distributions, and prerequisite indexes for each project simulation; (2) writing the system performance probability distributions prior to action evaluation and selection; (3) testing to see that any required actions have been selected; (4) calling subroutine VALUE to perform the evaluation of actions and select the "best"; (5) calling subroutine EXINFO, or ATINFO, which determines the new states of knowledge for the characteristics measured by the action selected; (6) recording the satisfaction of prerequisites; (7) deleting subordinate actions from those on the eligible list;* (8) updating the present time and cost; (9) recording the order of selection for the action just selected; (10) removing the action selected from the list of eligible actions; (11) testing for selection of a terminal action; (12) if action selected is not terminal, returning to select another action; (13) if action is terminal, identifying the system design chosen and calling OUTPUT to record the final state; and (14) returning to make another project simulation if the sample is not complete. The main program also writes messages for certain errors that may occur. These errors will not occur when the program is functioning properly.

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*This is done when an assemble and test is selected. In this case, perfect knowledge is obtained regarding all components of the system; hence, any action that would produce imprecise information regarding the components of the design that was assembled is unnecessary.

SUBROUTINE "INPUTS"

This subroutine reads the input data including the initial probability distributions for the characteristics of the fuselage and tail and the wing and nacelles.

SUBROUTINE "INITSP"

This subroutine determines the initial probability distributions for all characteristics of the airframe and the aircraft. It calls subroutine EQN303, EQN302, EQN301, EQN104, EQN103, EQN102, and EQN101.

SUBROUTINE "VALUE"

This subroutine performs a number of bookkeeping functions and calls subroutines to evaluate actions. The subroutine consists of a "Do Loop" ranging over all the actions. The flow of the subroutine is as follows: (1) The subroutine is entered with a low initial value for the maximization process. (2) An action is selected by the Do Loop. (3) If the action has been selected previously, it cannot be selected again and control returns to the start of the Do Loop; however, if the action has not been selected previously, control proceeds to the next step. (4) The activity category of the action is determined. If the action is from the "Deliver" category, control passes to Step 5a. If it is from the "Assemble and Test" category, control passes to Step 5b. Otherwise, control passes to Step 6c. (5a) If the prerequisite assemble and test action has not been previously selected, control returns to the start of the Do Loop. If the prerequisite has been selected, the control proceeds to Step 6a. (5b) If the prerequisite experiment actions have not been previously selected, control returns to the start of the

Do Loop; otherwise, control proceeds to Step 6b.* (6a) Subroutine VDELIV is called to determine the value of the action and control proceeds to Step 7. (6b) Subroutine VASSEM is called to determine the value of the action and control proceeds to Step 7. (6c) Subroutine VEXPMT is called to determine the value of the action and control proceeds to Step 7. (7) The value determined at Step 6 is compared to the previous high value, or the low initial value the first time through. If the value of the action being evaluated is greater than or equal to the previous value, then the present value is substituted and the action being evaluated is identified as the action to be selected. Control proceeds to the end of the Do Loop. (8) If all actions have not been evaluated, control returns to the beginning of the Do Loop; otherwise, control returns to the main program.

SUBROUTINE "EXINFO"

This subroutine identifies characteristics measured by an experiment action and samples the corresponding probability distributions to determine the new state of knowledge regarding the measured characteristics. Subroutine GAUSS is called.

SUBROUTINE "ATINFO"

This subroutine performs the same functions as EXINFO, but only for the characteristics measured by an assemble and test action.

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*Note that Step 5b is not present in Policy 2.

SUBROUTINE "UPDATE"

This subroutine determines the probability distributions for characteristics at the airframe and aircraft levels from lower level distributions. It is used for both updating after an action has been selected and for determining preposterior distributions. It calls subroutine EQN303, EQN302, EQN301, EQN104, EQN103, EQN102, and EQN101 in the proper order.

SUBROUTINE "VDELIV"

This subroutine determines values for deliver actions as described in Sec. IV.

SUBROUTINE "VASSEM"

This subroutine determines values for assemble and test actions as described in Sec. IV.

SUBROUTINE "VEXPMT"

This subroutine determines values for experiment actions as described in Sec. IV.

SUBROUTINE "EQN303"

This subroutine determines the mean and standard deviation for the airplane efficiency factor at the airframe level. It uses Eqs. (88) and (89).

SUBROUTINE "EQN302"

This subroutine determines the mean and standard deviation for the frictional drag coefficient at the airframe level. It uses Eqs. (91) and (92).

SUBROUTINE "EQN301"

This subroutine determines the mean and standard deviation for the weight of the airframe. It uses Eqs. (85) and (86).

SUBROUTINE "EQN104"

This subroutine determines the mean and standard deviation for the airplane efficiency factor at the system level. It uses Eqs. (97) and (98).

SUBROUTINE "EQN103"

This subroutine determines the mean and standard deviation for the frictional drag coefficient at the system level. It uses Eqs. (100) and (101).

SUBROUTINE "EQN102"

This subroutine determines the mean and standard deviation for the gross take-off weight of the aircraft. It uses Eqs. (94) and (95).

SUBROUTINE "EQN101"

This subroutine determines the mean and standard deviation for nautical miles per pound for the aircraft. It uses Eqs. (104) and (105).

SUBROUTINE "GAUSS"

This subroutine determines random numbers drawn from specified normal distributions. It is part of the IBM Scientific Subroutine

Package.[*] It calls subroutine RANDU.

SUBROUTINE "RANDU"

This subroutine determines uniform random numbers. It also is part of the Scientific Subroutine Package.[†]

SUBROUTINE "OUTPUT"

This subroutine writes the final states and sequences of actions of the simulation projects.

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[*] *System/360 Scientific Subroutine Package (360A-CM-03X) Version III Programmer's Manual*, 4th ed., H20-0205-3, International Business Machines Corporation, New York, 1968.

[†] Ibid.

Appendix D

MONTE CARLO VS PROPAGATION OF ERROR

There are two factors involved in the choice between using Monte Carlo methods (MC) and using the Propagation of Error method (PE) to determine aggregate uncertainty of error. These factors are the closeness between the results obtained using the two methods and the amount of computer time available. The reason that there may be differences between the results obtained with the two methods is that the probability distributions involved may not be normal. MC can be used with probability distributions having any form while PE requires that all distributions be normal; hence, in situations involving nonnormal distributions, MC calculations with large samples should yield results that are closer to "reality."

There are several factors that influence the normality of the probability distributions involved in any given study. One factor is the shape of the low-level distributions. In the present study, they are assumed to be normal. Three other factors relate to the shape of the aggregate distributions. These are the equations that specify the relationship(s) between the low-level variables and the high-level variables, the central values of the low-level distributions, and the spreads of the low-level distributions.

In the present study, all equations involved in the propagation of uncertainty calculations are linear except for the fuel economy equation. No significant difference between MC and PE is expected for linear equations because the partial derivatives of the high-level variables with respect to the low-level variables are all constants. Consequently, the evaluation will not depend on any mean values for low-level variables. To compare MC to PE for the fuel economy equation, Eq. (104), samples of 1000 calculations were made and the mean and standard deviation of the results were compared to the mean and standard deviation obtained using PE. Three different low-level uncertainties were used. The results are summarized in Tables 13 and 14. The gross take-off weight was also included as a check on the sampling process.

The results are, of course, dependent on the random number generator used. In the present study, the random number generator used is that contained in the IBM Scientific Subroutine package for the 360 series computers.* Given this means of generating normal random numbers, it was judged that Case I and Case II gave acceptable results and Case III did not.

The initial uncertainties for $C_{D_f A}$ and e_A that were used in this study are summarized in Fig. 7. All values are reasonably close to or less than the values for Case II.

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*Ibid.

Table 13

LOW-LEVEL PROBABILITY DISTRIBUTIONS USED TO COMPARE MONTE CARLO AND PROPAGATION OF ERROR

Variables	*Case I*	*Case II*	*Case III*
$E(C_{D_f S})$	.024	.024	.024
$\sigma(C_{D_f S})$	.0024	.0048	.0072
$E(e_S)$	.9	.9	.9
$\sigma(e_S)$	.09	.18	.27
$E(W_A)$	27000.	27000.	27000.
$\sigma(W_A)$	2700.	5400.	8100.

Table 14

RESULTS OF MONTE CARLO AND PROPAGATION OF ERROR CALCULATIONS FOR LOW-LEVEL UNCERTAINTIES

Variables	*MC*	*PE*	*MC-PE*	*(MC-PE) × 100/MC*
Case I				
E(NMI/LB)	.080908	.080982	-.000074	-.09
σ*(NMI/LB)*	.004428	.004240	.000188	4.24
E(GTO WT)	126888.	127000.	-112.	-.09
σ*(GTO WT)*	3019.	2700.	319.	10.57
Case II				
E(NMI/LB)	.080815	.080982	-.000167	-.21
σ*(NMI/LB)*	.009110	.008481	.000629	6.90
E(GTO WT)	126784.	127000.	-216.	-.17
σ*(GTO WT)*	5697.	5400.	297.	5.21
Case III				
E(NMI/LB)	.080612	.080982	-.000370	-.46
σ*(NMI/LB)*	.014798	.012721	.002077	14.04
E(GTO WT)	126679.	127000.	-321.	-.25
σ*(GTO WT)*	8453.	8100.	353.	4.18

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10. ABSTRACT

Proposes a technique for analyzing the effects of alternative engineering decisionmaking policies and alternative forms of military system development contracts. Each development project is characterized by goals set by a multiple-incentive contract; alternative component designs; possible engineering actions; and states of knowledge concerning (1) the relationship between the characteristics of components, subsystems, and the total system, and (2) the values of component, subsystem, and system characteristics. The procedure is a dynamic technical risk assessment. Specific engineering tests reveal probability distributions of characteristics. Subsequent actions are selected accordingly and their results evaluated, and so on until delivery. Propagation-of-error methods are used to determine the impact of the component-level forecast on the overall system and program. An example comparing 5 development policies for an antisubmarine patrol plane with 8 alternative configurations under 2 multiple-incentive contracts for 51 simulated project histories showed "maximize expected payoff" to be the best policy.

11. KEY WORDS

Contracts
Procurement
Aerospace Industry
Decisionmaking
Research and Development
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Computer Simulation